Maryland
Department of the Environment

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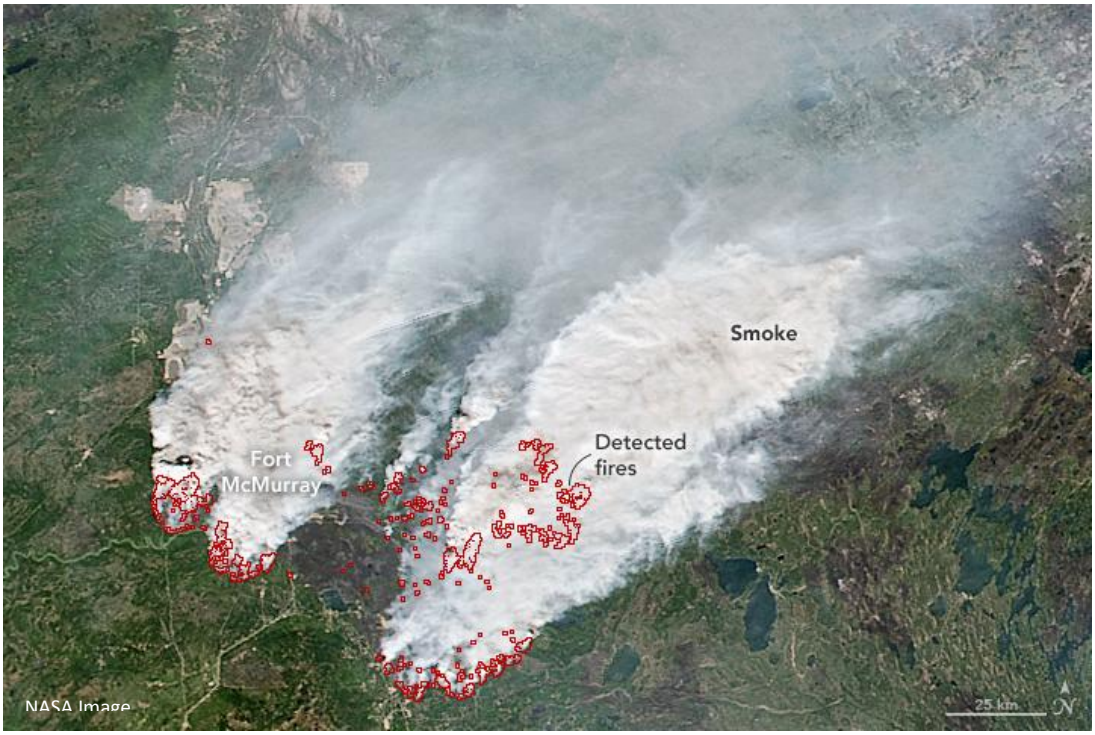
State of Maryland
Exceptional Event Demonstration and Analysis of the May 2016 Fort McMurray, Alberta Canada Wildfire and its Impact on Maryland's Air Quality on May 25 and 26, 2016



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i. Acknowledgements

The Maryland Department of the Environment (MDE) would like to thank the Connecticut Department of Energy and Environmental Protection (CT DEEP), Northeast States for Coordinated Air Use Management (NESCAUM), and EPA regions 1, 2 and 3 for the collaborative effort put forth in an event which impacted a wide area of the eastern United States simultaneously. Special thanks to Michael Geigert (CTDEEP) for his coordination of information and resources.

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1. Overview

1.1. Introduction

A wildfire near Fort McMurray in Alberta, Canada burned out of control through the month of May, 2016. During a particularly intense period of fire growth an expansive and concentrated smoke plume was lofted into the atmosphere and transported several thousand kilometers into the central United States (US). Upon photochemically aging, the wildfire smoke[1] produced widespread ozone across the upper Midwest and Great Lakes of the US and was then transported to the northeastern US. Ozone concentrations exceeded the 2015 70 ppb National Ambient Air Quality Standard (NAAQS) by May 23, 2016 across the central US. By May 25 and 26, 2016 ozone concentrations exceeding 70ppb were widespread across the northeast US and Maryland (Figure 1). In Maryland the maximum daily 8-hour average ozone (MD8AO) concentration reached a peak of 85 ppb with 16 of the 20 Maryland ozone monitors exceeding the 70 ppb standard on one or both days due to the influences of the Fort McMurray wildfire smoke. Those monitors that exceeded the 70ppb standard are highlighted in Table 1. Approximately 73% of the Maryland MD8AO concentrations during the two day event were among the four-highest 8-hour ozone observations of the 2016 season.

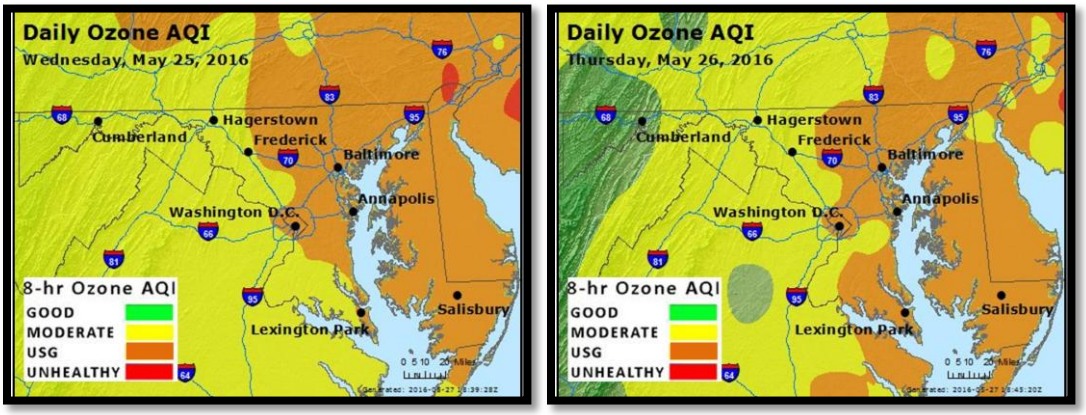

Figure 1. AQI maps from May 25 and 26, 2016.

Following the U.S. Environmental Protection Agency's (EPA) Exceptional Events Rule (Title 40 of the Code of Federal Regulations Part 50.14), the Maryland Department of the Environment (MDE, "The Department") flagged the data as being influenced by a Canadian wildfire and communicated to EPA Maryland's intention of submitting an exceptional event package for ozone on May 25 and 26, 2016. This analysis is to demonstrate that Maryland's 8-hour ozone concentrations that exceeded the 2015 standard meet the requirements for having been influenced by an exceptional event and should therefore be excluded from design value (DV) calculations used to determine Maryland's ozone attainment status.

1.2. Exceptional Events Summary of Approach

The Exceptional Events Rule as defined in 40CFR 50.14 states that an event may be excluded from regulatory use if it had the following characteristics:

[1]Smoke from biomass burning contains volatile organic compounds (VOCs) and nitrogen oxides (NOx), which react to form ozone.

1) There is a clear, causal relationship between the event and the monitored exceedance that affects air quality;

2) The event was of human origins not likely to recur or was natural in origins;

3) The occurrence was not reasonably controllable or preventable.

Table 1. Maximum 8-hour ozone concentrations and ranks on May 25 and 26, 2016 for all Maryland sites. Maryland sites are listed using the common site name and Air Quality System (AQS) identification number (AQSID). Also given are the maximum daily 8-hour average ozone (MD8AO) concentrations in ppb along with that day's rank in the 2016 ozone season in parentheses. A rank of (1) indicates the MD8AO was the highest recorded at that site in the 2016 season. The final columns indicate the current fourth high and design value with no exclusion of any data. Sites with an asterisk indicate the site does not have a valid design value in 2016. Monitors exceeding 70ppb during the event are highlighted in orange.

SiteName	AQSID	MD8AO [ppb] (rank)		2016	
		May 25	May 26	Fourth High [ppm]	Design Value [ppm]
Aldino	240259001	77 (3)	79 (2)	0.077	0.073
Beltsville CASTNET	240339991	76 (2)	72 (3)	0.070	0.068
Blackwater NWR CASTNET	240199991	70 (3)	76 (1)	0.068	0.066
Calvert	240090011	70 (4)	75 (1)	0.070	0.069
Edgewood	240251001	79 (4)	80 (2)	0.079	0.073
Essex	240053001	78 (4)	81 (2)	0.078	0.072
Fair Hill	240150003	83 (2)	76 (5)	0.080	0.076
Frederick	240210037	70 (4)	65 (8)	0.070	0.067
Furley	245100054	75 (4)	78 (2)	0.075	0.069
Glen Burnie	240031003	75 (6)	76 (4)	0.076	0.076*
Hagerstown	240430009	68 (5)	61 (18)	0.070	0.066
Horn Point	240190004	71 (2)	77 (1)	0.067	0.064
HU-Beltsville	240330030	74 (2)	74 (2)	0.070	0.069
Millington	240290002	85 (1)	76 (2)	0.072	0.070
Padonia	240051007	74 (3)	84 (1)	0.073	0.072
PG Eq Cntr	240338003	74 (5)	69 (8)	0.076	0.071
Piney Run	240230002	64 (7)	53 (39)	0.066	0.065
Rockville	240313001	69 (2)	67 (6)	0.068	0.068
South Carroll	240130001	72 (4)	75 (2)	0.072	0.068
S. Maryland	240170010	69 (7)	73 (4)	0.073	0.070

Finalized revisions to the Exceptional Events Rule were established by the EPA by October of 2016[2]. The revised rule describes the procedures for treating data which has been influenced by an exceptional event. These were further clarified in an Exceptional Events Guidance Document[3] promulgated about the same time. Accordingly, an exceptional events demonstration must include all the following elements:

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2 Federal Register / Vol. 81, No. 191 / Monday, October 3, 2016: Treatment of Data Influenced by Exceptional Events

[3]Guidance on the Preparation of Exceptional Events Demonstrations for Wildfire Events that May Influence Ozone Concentrations, Final, EPA, September 2016: https://www.epa.gov/sites/production/files/2016-09/documents/exceptional_events_guidance_9-16-16_final.pdf

1) A narrative conceptual model that describes the event(s) causing the exceedance or violation and a discussion of how emissions from the event(s) led to the exceedance or violation at the affected monitor(s);

2) A demonstration that the event affected air quality in such a way that there exists a clear causal relationship between the specific event and the monitored exceedance or violation;

3) Analyses comparing the claimed event-influenced concentration(s) to concentrations at the same monitoring site at other times. The Administrator shall not require a State to prove a specific percentile point in the distribution of data;

4) A demonstration that the event was both not reasonably controllable and not reasonably preventable;

5) A demonstration that the event was caused by human activity that is unlikely to recur at a particular location or was a natural event; and

6) Documentation that the submitting air agency followed the public comment process.

Furthermore, 40CFR50.14(b)(4) states that the EPA " … Administrator shall exclude data from use in determinations of exceedances and violations where a State demonstrates to the Administrator's satisfaction that emissions from wildfires caused a specific air pollution concentration in excess of one or more national ambient air quality standard at a particular air quality monitoring location and otherwise satisfies the requirements of this section. Provided the Administrator determines that there is no compelling evidence to the contrary in the record, the Administrator will determine every wildfire occurring predominantly on wildland to have met the requirements identified in paragraph (c)(3)(iv)(D) [item (4) above] of this section regarding the not reasonably controllable or preventable criterion."

The guidance document also recommends following a tiered based approach to the analysis, providing evidence of "Key Factors" in each tier. Following the elements suggested in the Exceptional Events Guidance Document[3] as outlined above, MDE contends and demonstrates here-in that the transported wildfire smoke had a direct role in amplifying ozone concentrations to a level which would not have been possible in the absence of smoke constituents and satisfies the three core exceptional event criterion. Based on recommendations from the EPA and the Guidance Document, Maryland used a Tier 3, weight of evidence approach for this analysis. MDE addresses each of the necessary elements cited previously in the subsequent sections of this document. EPA guidance offers suggestions for appropriate analyses to demonstrate the clear causal relationship between the wildfire and excessive ozone levels. In addition, EPA recognizes that appropriate levels of analysis will vary for particular locations and conditions. EPA does not intend for the guidance to constrain the analysis. MDE includes some of the suggested analytics and variations on those methods to support our conclusion that the high ozone concentrations throughout Maryland were caused or worsened by the wildfire smoke plume from the Fort McMurray fire in May of 2016.

1.3. Regulatory Significance of the Exclusion

1.3.1. May 2016 Exclusion Request

There are 20 ozone monitors in the state of Maryland (Figure 2) covering three different Metropolitan Statistical Areas (MSAs). MDE operates 18 of these regulatory ozone monitors while the EPA Clean Air Status and Trends Network (CASTNET) program operates the additional two monitors. On May 25 and 26, 2016 13 and 15 monitors, respectfully, exceeded the 70ppb ozone NAAQS across the state of Maryland and meet the criteria for further analysis and potential exclusion if given concurrence by the EPA that an exceptional event occurred, according to criteria listed in 40 CFR 50.14(a)(1)(i). MDE asks for exclusion of all the MD8AO observations above 70 ppb on May 25 and 26, 2016 as listed on Table 2. While MDE does not operate the CASTNET monitors, MDE requested the CASTNET monitor data be flagged by the Clean Air Markets Division (CAMD) of EPA (Appendix A), who responded by flagging the data for exclusion in this demonstration. Therefore Maryland asks for exclusion of 28 MD8AO observations between May 25 and 26, 2016 which exceeded 70 ppb at the following 16 monitors: Aldino (240259001), Calvert (240090011), Edgewood (240251001), Essex (240053001), Fair Hill (240150003), Furley (245100054), Glen Burnie (240031003), Horn Point (240190004), HU-Beltsville (240330030), Millington (240290002), Padonia (240051007), PG Eq Cntr (240338003), South Carroll (240130001), S. Maryland (240170010), and the two CASTNET sites – Beltsville (240339991) and Blackwater NWR (240199991). MDE requests that these observed ozone data on May 25 and 26, 2016 at these monitors as listed in Table 2 be flagged as impacted by an exceptional event and be excluded from regulatory use.

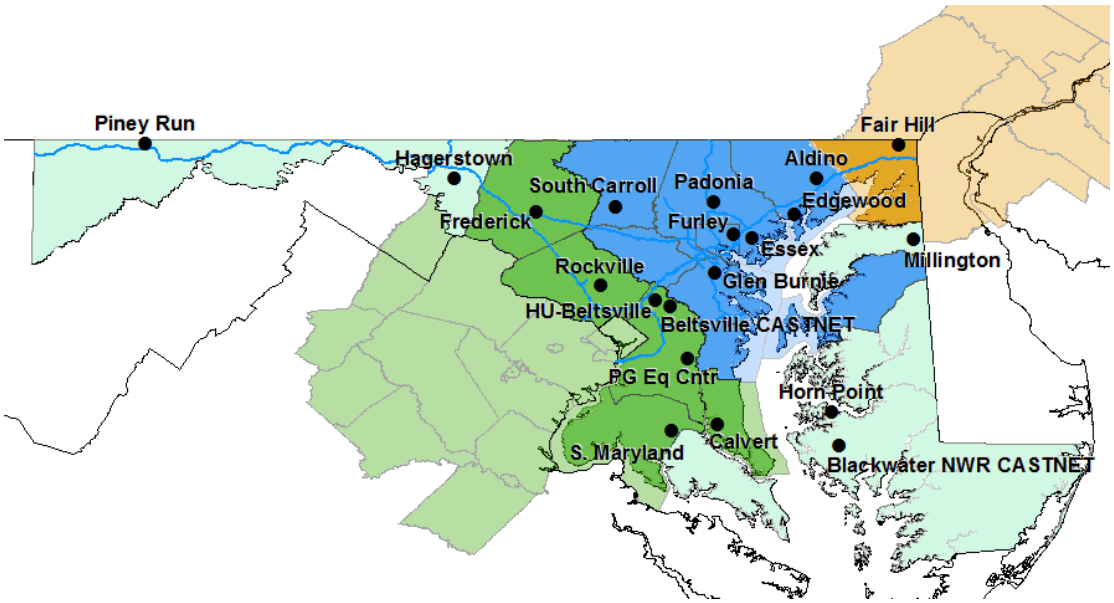


Figure 2. The Maryland ozone air quality monitoring network as of May 25, 2016. Black dots indicate the location of ozone monitors. Metropolitan Statistical Areas (MSAs) for Baltimore-Towson (Blue), Washington-Arlington-Alexandria (Green) and Philadelphia (Orange – Non-Attainment Area) show that Maryland monitors include three policy relevant areas and several states; all areas of which are above the new 70ppb standard. The Philadelphia MSA is in non-attainment of the old 2008 75ppb standard. The rest of Maryland is colored in light cyan. The blue lines show major interstates. Gray lines are county political boundaries. Other lines are state borders.

Table 2. Ozone monitors at which MDE is seeking EPA data exclusion concurrence.
Local names and Air Quality System (AQS) identification numbers (AQSID) identify monitors in the text. Also given are the maximum daily 8-hour average ozone (MD8AO) concentrations in ppb along with that day's rank in the 2016 season in parentheses. A rank of (1) indicates the MD8AO was the highest recorded at that site in the season. The final columns indicate the 2016 fourth high and design value with no exclusion of data (Including) and if the requested data from May 25 and 26 are excluded from fourth high and design value calculations (Excluding). Sites with an asterisk indicate the site does not have a valid design value in 2016. Cells showing "-" are MD8AO at sites which did not exceed 70ppb and therefore cannot seek exclusion.

		2016					
SiteName	AQSID	MD8AO [ppb] (rank)		Fourth High [ppm]		Design Value [ppm]	
		May 25	May 26	Including	Excluding	Including	Excluding
Aldino	240259001	77 (3)	79 (2)	0.077	0.076	0.073	0.073
Beltsville CASTNET	240339991	76 (2)	72 (3)	0.070	0.070	0.068	0.068
Blackwater NWR CASTNET	240199991	-	76 (1)	0.068	0.068	0.066	0.066
Calvert	240090011	-	75 (1)	0.070	0.069	0.069	0.068
Edgewood	240251001	79 (4)	80 (2)	0.079	0.079	0.073	0.073
Essex	240053001	78 (4)	81 (2)	0.078	0.077	0.072	0.072
Fair Hill	240150003	83 (2)	76 (5)	0.080	0.076	0.076	0.074
Furley	245100054	75 (4)	78 (2)	0.075	0.068	0.069	0.066
Glen Burnie*	240031003	75 (6)	76 (4)	0.076	0.076	0.076	0.076
Horn Point	240190004	71 (2)	77 (1)	0.067	0.067	0.064	0.064
HU-Beltsville	240330030	74 (2)	74 (2)	0.070	0.069	0.069	0.068
Millington	240290002	85 (1)	76 (2)	0.072	0.069	0.070	0.069
Padonia	240051007	74 (3)	84 (1)	0.073	0.073	0.072	0.072
PG Eq Cntr	240338003	74 (5)	-	0.076	0.076	0.071	0.071
South Carroll	240130001	72 (4)	75 (2)	0.072	0.068	0.068	0.067
S. Maryland	240170010	-	73 (4)	0.073	0.073	0.070	0.070

1.3.2. Design Value and Fourth High Impacts

Exclusion of the MD8AO concentrations on May 25 and 26, 2016 lowers the DV at several monitors in Maryland. The EPA designates an area's attainment status of the NAAQS via the DV metric. For 8-hour ozone, each monitor's annual fourth-highest daily 8-hour maximum concentration averaged over the past three years designates the attainment status for that particular area. Ozone concentrations on May 25 and 26 were within the fourth-highest 8-hour average observations of 2016 at eighteen monitors (Table 1). Excluding the May 25 and May 26 MD8AO at the 16 requested monitors (Table 2) would reduce six (6) monitors' DV, including the Fair Hill monitor (240150003), which would drop below the 2008 75 ppb NAAQS level (from 76 to 74 ppb). Details of specific site DVs with and without exceptional event status along with changes in the fourth highest MD8AO concentrations for the 2016 season are provided in Table 2 for all 16 Maryland monitors that MDE is requesting exceptional event status. While no additional monitors would be classified as attainment of the 2015 70 ppb standard, reduction of these sites' DV would potentially be used

to demonstrate compliance through 2018. While MDE acknowledges the EPA's interpretation of 40 CFR 50.14(a)(1)(i), MDE also recognizes the importance of the fourth highest value in a given year potentially determining future year DVs. While not currently requesting sites based solely on these fourth high values, those monitors which observed one of their fourth highest ozone concentrations during the two day event but did not exceed the 70ppb standard are listed in Appendix B.

Excluding the ozone concentrations associated with the May event will impact not only DVs in 2016, but also 2017 and 2018, particularly considering another wildfire smoke plume impacting Maryland in July (MDE will present this exceptional event in another demonstration). Excluding all the requested MD8AO concentrations associated with the May event will reduce six monitor's DVs immediately in 2016. In addition, it will reduce a total of eight monitors' 2016 fourth high MD8AO and have future implications in 2017 and 2018. For example, an EPA concurrence of the May exceptional event at Aldino (240259001) changes its fourth high from 0.077 to 0.076ppm, but does not reduce Aldino's 2016 DV. However, if the July exceptional event demonstration receives EPA concurrence at Aldino, the fourth high is reduced an additional 0.02 ppm and the 2016 DV drops 0.01 ppm to 0.075 ppm. If May does not receive EPA concurrence, there is no ramification at the Aldino site if only July receives concurrence.

1.3.3. NAAQS Attainment Considerations

EPA concurrence of the requested MD8AO observations on May 25 and 26, 2016 in Maryland will bring the Fair Hill monitor (240150003, Philadelphia Non-Attainment Area (NAA)) into attainment of the 2008 ozone standard. At this time only the Fair Hill monitor would be re-classified as attainment of the 2008 NAAQS should EPA concur with Maryland's May exceptional event demonstration. However, the Fair Hill monitor is part of the Philadelphia-Wilmington-Atlantic City, PA-NJ-MD-DE NAA and EPA would need to concur with the Exceptional Event demonstration submitted by Pennsylvania Department of Environmental Protection (PA DEP) for the NAA to be found attaining the 2008 ozone NAAQS. It is therefore uncertain if the Philadelphia NAA will achieve attainment of the 75 ppb standard even if EPA concurs with MDE's demonstration. The EPA evaluation of the May exceptional event in the Philadelphia-Wilmington-Atlantic City, PA-NJ-MD-DE NAA would potentially affect its designation status, which is due later in 2017. In any case the Philadelphia-Wilmington-Atlantic City, PA-NJ-MD-DE area would still be classified as non-attainment of the 2015 ozone NAAQS. All other Maryland monitors are attaining the 2008 standard currently; no monitor's attainment status of the 2015 70 ppb standard will change. However, depending on future year ozone concentrations, this demonstration may significantly impact Maryland's attainment status in regards to the 2015 ozone NAAQS.

The Baltimore, Maryland area needs to demonstrate continued attainment of the 2008 ozone standard by 2018. This continued attainment of the 2008 ozone standard might only occur if EPA concurs with this exceptional event demonstration for May 25 and26, 2016. In addition, if EPA does not concur with this exceptional event determination the Baltimore area designation might change as a result.

1.4. Summary of Findings

This report demonstrates that:

- There was a clear causal relationship between the smoke and the MD8AO exceedances;
- The wildfire causing smoke was considered a natural event;
- The smoke events in question were not reasonably preventable and are unlikely to recur;

Key findings and evidence supporting these assertions include the following:

- Copious ozone was generated upstream of Maryland due to the presence of wildfire smoke then transported into the state.
- Ozone higher than historical norms within an environment of historically low anthropogenic precursors.
- A Q/d analysis which does not meet EPA thresholds for clear causal influence but is consistent with other previous long range smoke and ozone transport events from Canada to Maryland.
- Fine Particle ($PM_{2.5}$), Carbon Monoxide and Nitrogen Oxides (NOx) were elevated during the event, which are consistent with a wildfire smoke plume.
- $PM_{2.5}$ speciated data showed elevated wildfire attributable concentrations.
- Satellites captured a visual smoke plume transported to the northeastern US which was also associated with satellite retrieved CO, both which tracked from the Fort McMurray area.
- Similar day analysis showed similar days in previous years did not yield as much ozone.
- Photochemical modeling during the event showed a significant under prediction due to the absence of gaseous wildfire emissions within the ozone chemistry of the model.

Several analysis methods were used to develop a weight of evidence demonstration that the 8-hour ozone concentrations above 70 ppb in the May 2016 event meet the rules for data exclusion as an Exceptional Event. In summary, satellite, meteorological data, trajectory analysis, emissions data, speciated $PM_{2.5}$ data, and numerical air quality model comparisons were used to assess whether conditions were favorable for transport of smoke from the Fort McMurray Canadian wildfires to monitors that showed 8-hour ozone concentrations above 70 ppb. The data also showed that the transported smoke degraded air quality northwest (upstream) of Maryland first, then this photochemically aging airmass was transported eastward, creating a prolonged period (May 21-28) of enhanced ozone from the Mississippi River eastward to the east coast, including Maryland.

Substantial changes in chemistry in the eastern United States due to regional NOx emissions reductions have occurred over the last decade. The following analysis puts the 8-hour ozone concentrations in Maryland during this ozone event in the context of these reductions and in comparison to ozone in previous months of May. Comparison of emissions during late May of 2016 show Electric Generating Unit (EGU) NOx emissions were lower than any other year on record during the smoke event. Yet, ozone concentrations in May of 2016 exceeded ozone concentrations in earlier years during similar meteorology and under heavier anthropogenic precursor emissions. Analysis of the airmass associated with the Maryland ozone exceedances on May 25 and 26, 2016 revealed a composition characteristic of wildfires with an abundance of ozone precursors despite substantial reductions in anthropogenic sources.

MDE's analysis strongly supports that all monitors, regardless of MD8AO concentration, were impacted by smoke, that all the MD8AO concentrations above 70ppb in Maryland from May 25 and 26, 2016 meet the rules as an Exceptional Event, and the 16 monitors and 28 MD8AO observations in Table 2 should be excluded from DV calculations. The following documentation justifies these claims and is outlined as follows: Section 2 contains a conceptual model overview of the event including a synopsis of the meteorological and air quality conditions, emissions, transport and characteristics defining the event. Section 3 demonstrates a clear causal relationship between the exceedance via a tiered, weight of evidence approach. Section 4 demonstrates that this event fulfills the definition of a natural event that is unlikely to recur while Section 5 fulfills the requirements that demonstrate the event was not reasonably controllable or preventable. Section 6 documents the public comment process while section 7 summarize and concludes the analysis.

2. Conceptual Model and Overview of the May 21-28, 2016 Smoke and Ozone Event

2.1. Maryland Area Description

As part of the Clean Air Act (CAA), both local and state air quality agencies are required to maintain and operate ambient air quality monitoring networks. MDE complies with all EPA regulations defined in 40 CFR Part 58 and maintains a dense network of in situ and remote sensing pollution sampling platforms in Maryland. Surface monitors used for regulatory purposes include 20 ozone monitors as of May 25, 2016 (Figure 2) (including two EPA CASTNET sites, (EPA, 1997)), nine hourly fine particle ($PM_{2.5}$) Beta Attenuation Monitors (BAMs) with additional regional coverage of ozone and $PM_{2.5}$ hourly observations locations in Washington D.C. (DC) and northern Virginia, as well as various $PM_{2.5}$ Federal Reference Method (FRM) filter speciations, VOC canisters and three 915 MHz radar wind profilers (RWP; Ryan, 2004; MDE, 2015) in Maryland. A full description of the various instrumentation used by MDE is available in the MDE Network Plan (MDE Ambient Air Monitoring Plan, 2017).

The dense MDE network exists to account for a densely populated area of the United States between DC and Baltimore. The distribution of ozone monitors across the state favors the I-95 corridor (blue line running southwest to northeast from DC to just south of the Fair Hill ozone monitor on Figure 2), which stretches across the central part of the state from DC to along the northern portion of the Chesapeake Bay. Approximately 9,000,000 people reside along the I-95 corridor (including DC and northern Virginia) as of 2012. Statewide, Maryland's population was estimated to be 6,000,000 as of 2016 by the US Census Bureau. The state of Maryland also has diverse geography, with mountains greater than 2,000 ft to the west and coastal plains near sea level to the east that border the Chesapeake Bay and Atlantic Ocean. Outside of urban areas, Maryland is characterized by a mix of farmland to the east and mainly deciduous forests in the mountains to the west. The dynamic interplay between the dense population and diverse geography, particularly biogenic emissions, lee side subsidence by the mountains, and land/water interaction gives

Maryland distinct and variable air quality issues, which previously gave the Baltimore, Maryland area the distinction of having the highest reading ozone monitor (Edgewood; 240251001) along the US East Coast.

2.2. Characteristics of Typical, Non-Event Ozone Formation

Over the past two decades MDE has contracted with universities in and around Maryland to conduct thorough research of air quality in Maryland. In particular this collaboration has focused on the origin of ozone in Maryland. This research was done utilizing balloon-borne ozonesondes and airplane flights to capture vertical profiles of atmospheric composition. Computer modeling based on these observations further enhanced our understanding of the origin of ozone in Maryland. The understanding garnered from years of vertical and surface ozone measurements indicated a significant fraction of ozone and ozone precursors observed in Maryland were due to transport by winds from upstream states into Maryland which mixed with and compounded local emissions issues. Major legislation resulting from conclusions of this research resulted in robust changes in the air composition in the eastern United States over the past 10 years. Full details of this ongoing collaboration may be found on the RAMMPP[4] webpage. The following describes the current understanding of ozone formation in Maryland.

In the absence of a-typical airmass composition (e.g. exceptional events, smoke plumes), ozone formation in Maryland occurs primarily due to the photolization of volatile organic compounds (VOCs) and a combination of regional and locally sourced anthropogenic NOx in the presence of sunlight. The combination of high density population (pollution sources) and topography often focuses these reactions in well-defined areas that have historically created ozone issues east and northeast of DC and Baltimore. The main sources of anthropogenic emissions contributing to these issues are stationary point sources such as EGUs, mobile sources (cars, trucks, boats, locomotives and non-road equipment), and area sources that include industrial processes and consumer products. The urban pollution plumes that develop along the I-95 corridor between DC and Baltimore (mobile, industrial, area) and surrounding point sources (EGUs) constitute the overwhelming percentage of locally sourced NOx which contributes to Maryland ozone formation. These emissions alone regularly fall short of producing ozone capable of MD8AO concentrations above 70 ppb in Maryland. Photochemical modeling supports the assertion that exclusive of light winds and recirculation which build up the local emissions, Maryland EGU and mobile emissions are not great enough to support ozone exceedances. However, Maryland is also at the “tail pipe” end of the EGU rich Ohio River Valley (ORV) where a high density of large EGU point sources create a regional NOx plume upstream that transports NOx and/or ozone in to Maryland. The majority of Maryland exceedances historically have been associated with such transport. Thus the amount of ozone and ozone precursors (typically NOx) within the residual layer (layer of air immediately above the surface, typically around 500-2000m above ground level) transported into Maryland adds to and raises local Maryland ozone concentrations to and above NAAQS thresholds. Without significant transport, Maryland no longer observes wide spread or frequent ozone exceedances of the NAAQS.

In the past four years, Maryland has had few cases of pollutant transport comparable to historical (pre-2013) norms. In these recent years (2013-2016), the amount of ozone/precursors within the residual layer

[4] Regional Atmospheric Measurement Modeling and Prediction Program (RAMMPP): http://www.atmos.umd.edu/~rammpp/

has declined to the lowest levels ever recorded, leading to a reduction of maximum ozone concentration on any one day in Maryland and thus a decrease in the number of ozone exceedance days. This has caused local effects (meteorology, emissions) which previously were overwhelmed by regional signals to become more prominent, but overall has made exceedances isolated spatially and infrequent in occurrence at all NAAQS levels (Figure 3). Point source NOx emissions from states upstream of and including Maryland (Maryland, DC, Virginia, West Virginia, Pennsylvania, Ohio, Indiana – "Total NOx" in Figure 3) have dropped to record low levels each of the last three consecutive years. Said simply, EGU NOx emissions as a whole in 2016 were the lowest ever in states upstream of and including Maryland for the ozone season as a whole and for each month through the season, representing a total regional anthropogenic NOx decrease of nearly 50% in the past six years (Figure 4). Despite increasing vehicular traffic and vehicle miles traveled, NOx from mobile sources also has decreased over the same period, though the magnitude decrease is dwarfed by the EGU NOx decrease. However, even while mobile NOx has decreased less than EGU NOx, current Maryland mobile emissions, even with added local EGU emissions, are incapable of all but isolated, infrequent ozone exceedance days in Maryland on their own.

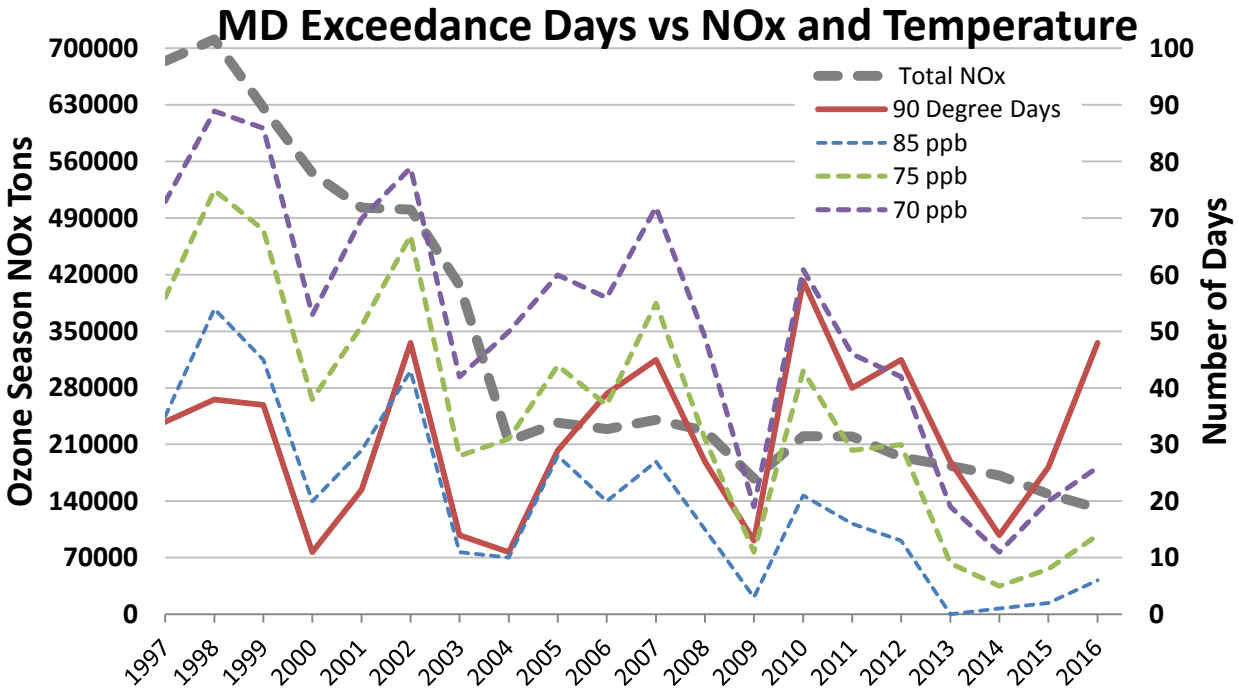


Figure 3. Total Ozone Season EGU NOx from Maryland and upwind states, number of days at or above 90°F at Baltimore-Washington Airport (90 DD) and exceedance days at various standards.

2.2.1. Emissions Trends

The Clean Air Markets Database (CAMD) records NOx output from EGU point sources across the country. In the typical, non-exceptional event model of a Maryland ozone exceedance day described above, transport of NOx into the state was primarily from upwind EGU point sources which vertically mixed ozone or ozone precursors (NOx) downward the next day to produce high concentrations of ozone which added to local

emissions. Significant and sustained reductions in NOx across the eastern US have occurred in the past 10-15 years (Figure 3). Aggregate NOx emissions from upstream areas are only 25% of their pre-2003 amounts in 2016, a reduction of approximately 75%. Aggregate monthly total NOx emissions in the 2016 ozone season (May - September) were the lowest ever observed from upwind states, which included Indiana, Ohio, West Virginia, Virginia, Pennsylvania, and the District of Columbia (also including Maryland), as shown in Figure 4. These states represent an area which contributes to the amount of ozone or ozone precursors transported into Maryland under typical summer conditions where the Bermuda High moves over the southeastern US. The month of May, 2016 observed roughly half the NOx emissions from these areas compared to 2010 and 2011.

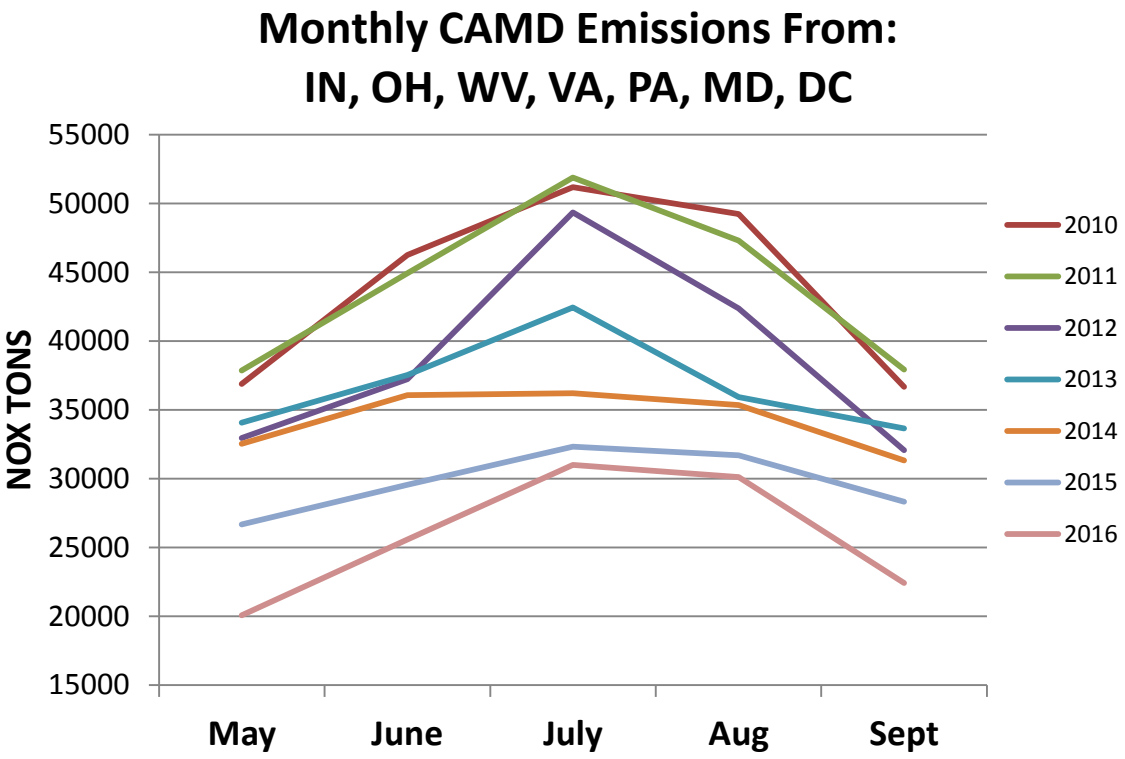


Figure 4. Monthly NOx emissions aggregated from the group of upwind states, including Maryland, by month of ozone season.

Daily emissions for the same states reflect the same reductions. Daily aggregate NOx emissions of Indiana, Ohio, West Virginia, Virginia, Pennsylvania Maryland and the District of Columbia for only the month of May from 2010 – 2016 pulled from CAMD showed emissions during May 2016 were the lowest ever (blue line, Figure 5). Generally there is also a downward trend, most notable in 2015 and 2016. There is a noted increase in emissions toward the final 10 days of the month each year when many EGUs come online for the summer season. Even still, the late May increase in NOx emissions in 2016 was the lowest daily late May emissions in the record. Even with these record low emissions in May of 2016, Maryland recorded two consecutive days of near-record high ozone in the state for the month of May (red outlined bars, Figure 5) and had two consecutive days of the greatest number of monitors exceeding 70 pbb since 2010 (black bars, Figure 5) on May 25 and 26, 2016.

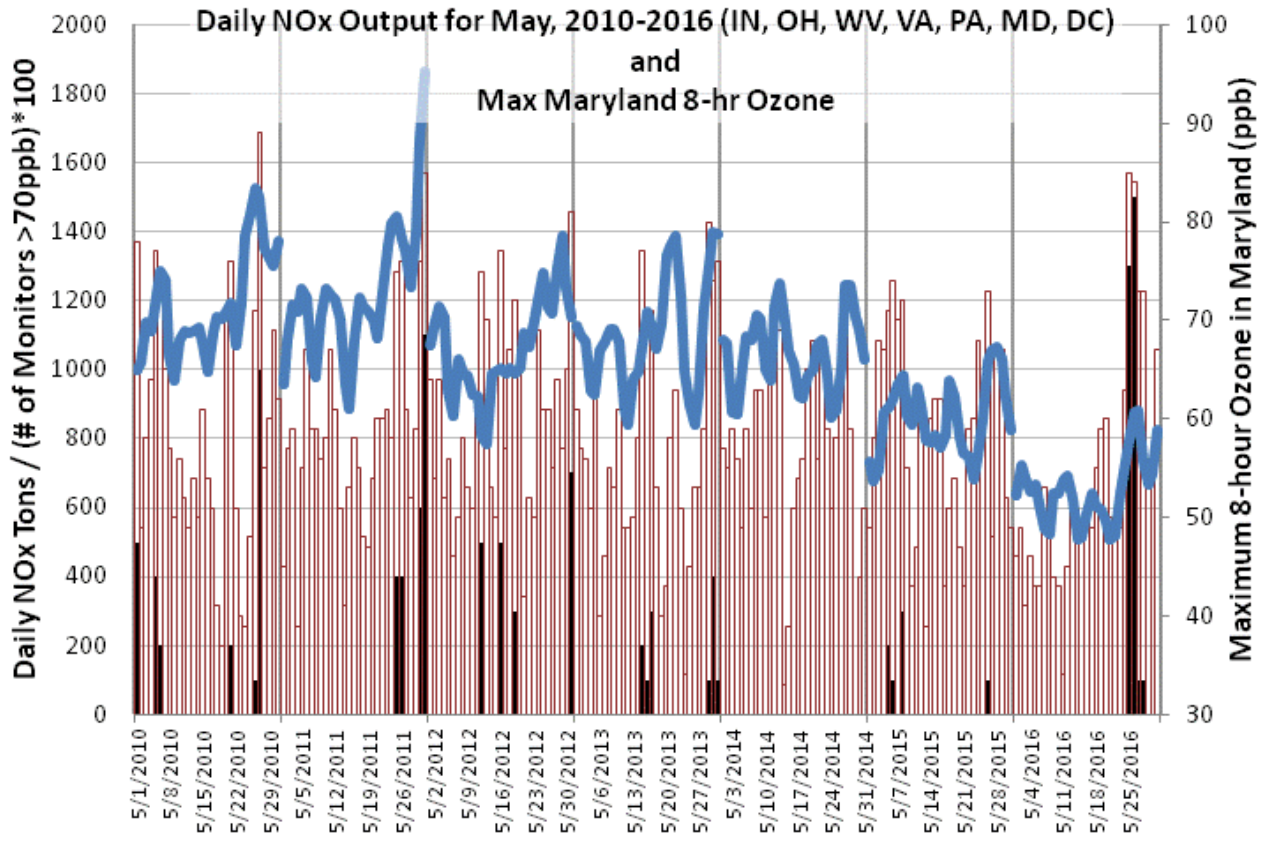


Figure 5. Daily aggregate NOx, maximum Maryland ozone, and monitors exceeding 70ppb in May, 2010-2016. Aggregate NOx emissions from EGU point sources for states upwind of Maryland (Indiana, Ohio, Pennsylvania, West Virginia, Virginia, DC and Maryland) from the CAMD database for 2010 – 2016 are shown with a thick blue line. The maximum 8-hour average ozone at any monitors in Maryland for each day in May 2010-2016 (red hollow bars) and the number of monitors exceeding 70ppb in Maryland (black bars x 100) is also shown. Number of exceeding monitors is multiplied by 100 for scale purposes. A downward trend in emissions is noticeable from 2014-2016. An increase in NOx emissions towards the end of the month each year is apparent but the 2016 increase is the smallest increase in the CAMD record. Each year/month is divided by a solid vertical line.

2.2.2. Ozone Production in Maryland

Research has found ozone production in Maryland to be a complicated mix of VOCs and NOx and that the atmospheric stoichiometry (the balance of concentrations necessary to produce bi-products like ozone) can change on a daily basis. Previously the balance of either precursor group was insignificant to their absolute measure in the atmosphere; both precursors were always in abundant supply for ozone exceedances and were simply dependent on weather. For example, the variability in exceedances in Figure 3 at 70ppb is strongly correlated (R^2 = 0.51) to the number of 90°F days from 1997 to 2015. However, adding just 2016, one of the hottest years of the past three decades, decreases this correlation (1997-2016: R^2 = 0.40). Maryland now exists in the NOx limited regime due to regional NOx reductions. The stoichiometry of the ozone production is no longer balanced and daily ozone production is instead based on the daily availability

of either of these precursor groups and/or the amount of ozone already formed upstream which is transported into the state. As a secondary consequence, hot temperatures are no longer a reliable predictor of daily ozone exceedances of the NAAQS.

Ozone production is controlled by the relative availability of NOx, VOCs, with ample heat and sunlight. VOCs relevant to ozone production in Maryland are both naturally occurring and anthropogenic. A significant but lesser decrease in anthropogenic VOCs was observed concurrent with NOx reductions. However, daily ozone production due to biogenic (naturally occurring) VOCs cannot be regulated and remain important to ozone production chemistry in Maryland. Isoprene, for example, a naturally occurring VOC, has the highest maximum incremental reactivity (i.e., easily makes more ozone) of VOCs tested in Maryland and is the highest VOC contributor on high ozone days. Isoprene is released by the biosphere (i.e., trees) due to environmental stresses such as heat. NOx output also increases from stationary sources on warm summer days in response to increased energy demand. Mobile emissions are not dependent on temperature and are relatively constant between workdays; Mobile emissions' impact on ozone generally decreases on the weekend. At the same time that relative NOx output increases, biogenic VOCs are released into the local environment, and, in the presence of sunlight and heat, create local ozone. When ozone and ozone precursors transported into the state combine with these local emissions, Maryland observes MD8AO above 70ppb and exhibits its fundamental non-event ozone exceedance. In this NOx limited regime, without additional transported ozone or ozone precursors, Maryland's local emissions are insufficient to produce ozone exceedance days.

2.2.3. Weather Patterns Leading to Ozone Formation

Summertime meteorology is variable in Maryland. Occasional April ozone exceedance days are possible, but most of the ozone exceedance days occur primarily from May through September. The intra-seasonal variations of weather that occur through the ozone season therefore result in various meteorological patterns conducive to ozone formation. In no specific order, the generic patterns are lee-side troughing (where downward air motions in the lee of the Appalachian Mountains induces an area of pollutant convergence along I-95 [parallel to the mountains]), airmass/ozone/pre-cursor transport, and local recirculation and stagnation (to include reverse [from the northeast] I-95 corridor flow). Ozone production in each pattern depends on ozone conducive local weather conditions (i.e., warm, sunny conditions with light to moderate surface winds). The location of the Bermuda high ultimately determines which, if any, of these scenarios develops. Average summer conditions place the Bermuda High off the southeast Atlantic coast of the US, which gives Maryland westerly (south-southwest to north-northwest depending on height) transport of upstream air. Lee-troughing is dependent on weak (<15 kts) cross-mountain flow around 850mb creating compressional heating/column stretching in the lee of the mountains. This induces a "trough" of lower pressure which often aligns with the I-95 corridor. Convergence along the trough increases ozone concentrations there. Both transport and lee troughing patterns may occur simultaneously or independently of each other. Assuming at least some downward mixing of transported ozone, lee-troughing may lead to an ozone exceedance day. Recirculation and stagnation over several days can also cause local pollution concentrations to increase to levels exceeding the NAAQS. All three of these patterns

are most probable during the summer months of June through August which, historically, were the climatological maximum for ozone production in Maryland. Shoulder seasons (Spring and Fall) typically are not warm enough and have active weather patterns preventing local or regional emissions from building. Winter is too cold for ozone exceedances and Maryland's Appalachian peaks are too low for Stratospheric ozone intrusion that could lead to an ozone exceedance day.

Differential heating at the land and water interface recirculates local and transported pollution near coastal areas via a thermally driven solenoidal circulation. Such circulations are believed to be the cause of high ozone DVs northeast of Baltimore. With increasing temperatures, super-regional NOx output increases from upstream EGUs in locations such as the ORV and western Pennsylvania, increasing residual layer concentrations of ozone and ozone precursors. These mix downwards at later times, combining with local sources, contributing to Maryland's ozone exceedances. This downward mixing is enhanced by the solenoidal circulation of the Chesapeake Bay Breeze (BB). Then lower mixing heights over the water "overcook" the precursors, creating greater concentrations over the Bay than nearby land sites. As a result, coastal sites achieve greater ozone concentrations as both regional and local emissions are concentrated by the land/water meteorology. It is no coincidence that the area of peak ozone in Maryland during a typical non-event ozone exceedance is northeast of Baltimore where local I-95 corridor emissions (the urban plume) are enhanced by transported regional pollution concentrated by land-water meteorology dynamics.

2.3. Exceptional Event Description: May 2016 Fort McMurray Wildfire

Abnormally warm and dry conditions across central Canada in late spring of 2016 promoted wildfire conditions in the provinces of Alberta and Saskatchewan. On May 1, 2016 a wildfire was spotted 15 km southwest of Fort McMurray, Alberta. A Provincial State of Emergency was declared and in the next few days the fire consumed 10% of the town of Fort McMurray, forced the evacuation of 80,000+ residents and came to be known as "The Beast." The fire was still burning out of control through mid-June before it was no longer expected to grow and was not fully extinguished until July 2016 though smoldering continued for many additional months. The cause of the fire is under investigation, but human activity is suspected[5]. Over 2,000 firefighters battled this and other wildfires across the province of Alberta. By May 19, 2016, the fire was estimated to have burned 505,645 hectares (1.25 million acres), was burning out of control and experienced a significant increase in size in just 48 hours. Firefighters from South Africa, the United States, and Canada assisted local teams battling the blaze. By June 10, 2016 589,995 hectares (1.46 million acres) had burned and approximately 2500 firefighters had battled various blazes across the province[6]. Amid "The Beast" at Fort McMurray, Alberta, which was spreading eastward in to Saskatchewan, dozens of additional fires were analyzed by the NOAA Daily Hazard Mapping System (HMS) smoke analyses (McNamara, et al., 2004) in southern Saskatchewan and the north central US by May 17 and 18 (Figure 6). Fires and associated smoke plumes analyzed by HMS were derived from the GOES Imager, the POES AVHRR, MODIS satellites and expert subjective analysis. Additionally, a large number of fires were ongoing across Mexico in mid-late May with a large concentration located in the Yucatan Peninsula (Figure 6). All fires across southern Canada and Mexico were dwarfed by the size of the Fort McMurray fire. While the collection of smaller fires still produced noticeable amounts of smoke which may have had some contribution to the plume which moved

[5] http://www.cbc.ca/news/canada/edmonton/fort-mcmurray-wildfire-cause-investigation-rcmp-1.3635241

into the northeast US on May 25 and 26, their fractional impact has been ignored in this demonstration. The analysis for the remaining demonstration will focus on the emissions from the Fort McMurray fire alone, which was extremely large, long-lasting, and produced a prolific smoke plume (Figure 7) that was created from a burn area larger than the US state of Rhode Island (Figure 8). News outlets reported impacts from the fire in New England and all the way to Spain.

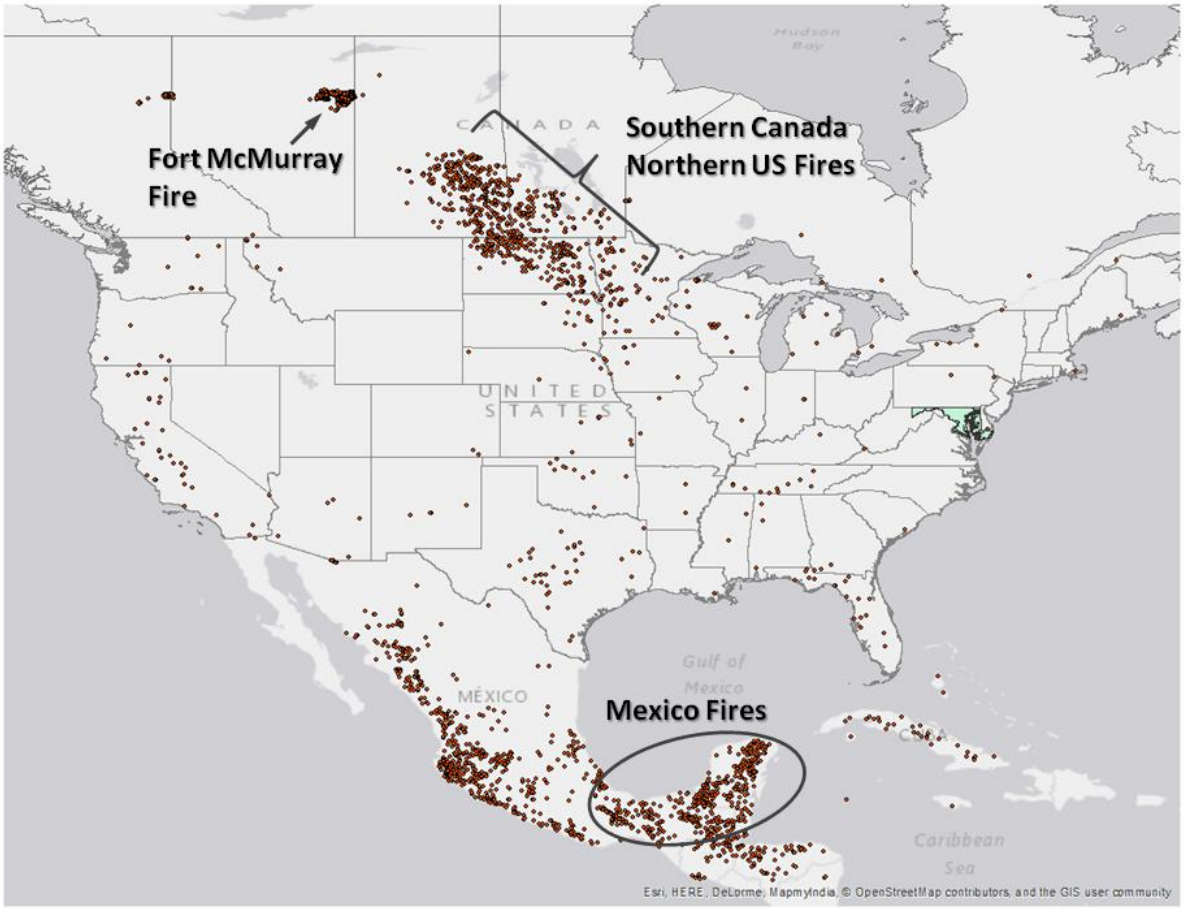


Figure 6. Hazard Mapping System (HMS) analyzed fires, May 17-20, 2016
Fires analyzed by HMS derived from the GOES Imager, the POES AVHRR, MODIS satellites and expert subjective analysis between May 17 and May 20. The Fort McMurray fire, southern Canada and Mexican fires referenced in the text are labeled accordingly. Maryland has been colored emphasize its location compared to the fire sources.

Figure 7. Fort McMurray Fire.
Image showing the immense, thick and elevated smoke plume from the fires near Fort McMurray. http://globalnews.ca/news/2685123/in-photos-the-fort-mcmurray-fire-that-displaced-80000-people/ [Source: Scott Olson/Getty Images; globalnews.ca]

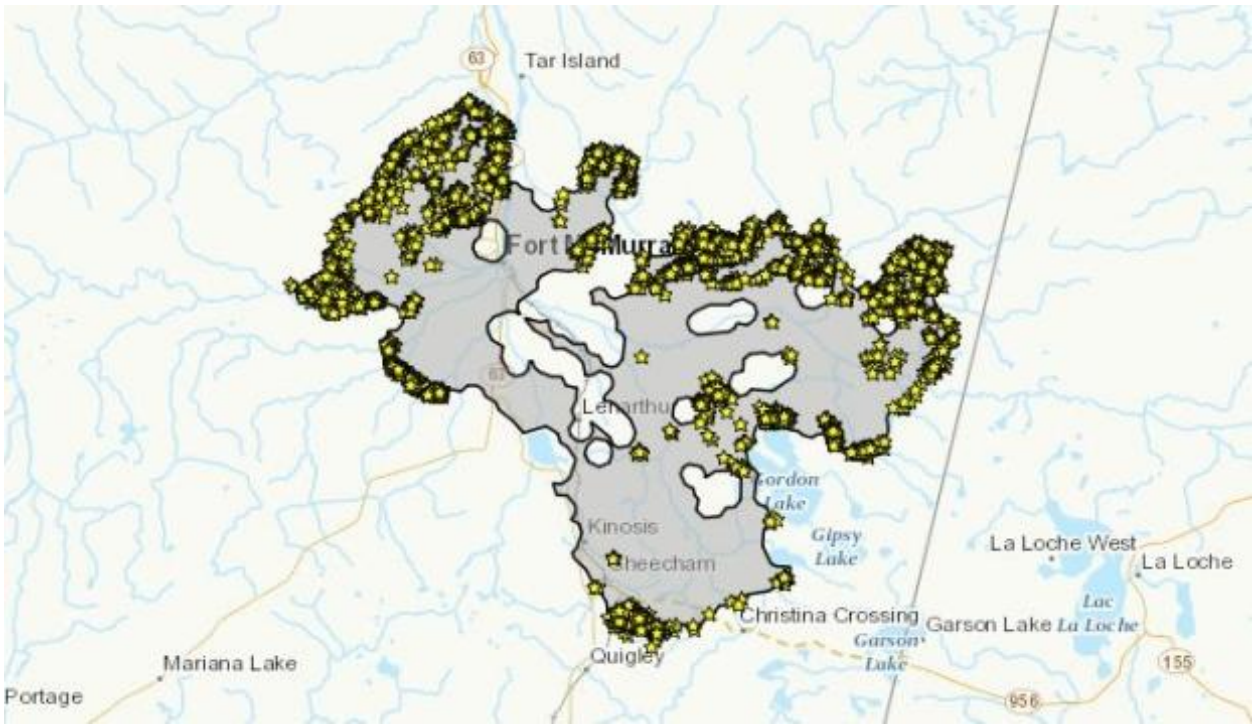


Figure 8. Fort McMurray fire extent as of May 17, 2016.
The size of the area in gray is larger than the size of state of Rhode Island. [Natural Resources Canada]

2.4. Conceptual Model of Ozone Formation from May 2016 Fort McMurray Fire

2.4.1. Overview and Literature Review

Wildfires are known sources of emissions responsible for both primary and secondary pollutants including CO, $PM_{2.5}$, NOx, VOCs, as well as ozone (Andreae and Merlet, 2001; McKeen et al., 2002; Bytnerowicz, et al., 2010). Similar to the study presented here, Canadian wildfires have increased ozone concentrations in Houston, TX (Morris et al., 2006) and as far away as Europe (Spichtinger et al., 2001). Evidence of Canadian wildfire smoke and biomass burning affecting the Mid-Atlantic's particulate matter (PM) air quality was also previously reported (Adam et al., 2004; Colarco et al., 2004; Sapkota et al., 2005) but wildfire smoke has also been recognized in high-ozone events on the east coast (Fiore et al., 2014). DeBell et al., (2004) presented a chemical characterization of the July 2002 Quebec wildfire smoke plume and its impact on atmospheric chemistry in the northeastern US. Most recently, Dreessen et. al., (2016) presented a case where a Saskatchewan, Canada wildfire smoke plume amplified ozone in Maryland in June of 2015, similar to the May 2016 case presented here. While relatively infrequent in the Mid-Atlantic, wildfire smoke has been an increasing fractional contribution to high-ozone exceedance days, particularly in light of increased fire frequency in a warming climate (Flannigan and Wagner, 1991; Marlon et al., 2009; Westerling et al., 2006; Spracklen et al., 2009; Pechony and Shindell, 2010), decreasing regional NOx emissions (Gégo, et al., 2007) and tighter ozone NAAQS (http://www3.epa.gov/ozonepollution/actions.html).

2.4.2. Ozone Generation from the Fire

Dreessen et. al. (2016) previously showed that smoke plumes from Central Canada are capable of transporting ozone to the Mid-Atlantic and causing NAAQS exceedances, even in the contemporaneously low NOx emission environment. As in the June 2015 ozone case covered in Dreessen et al., (2016), the May 2016 ozone event across the northeast US was characterized by a smoke plume associated with ozone concentrations increasing as the smoke plume aged. The ozone was transported into Maryland after being produced in a modified airmass upstream of Maryland.

In the 2015 case study examined by Dreessen et al. (2016), it was hypothesized that once the smoke-sourced VOC-rich plume interacted with anthropogenic NOx sources that copious ozone production began, which was capable of being transported long distances as either ozone or within ozone reservoir species. Dreessen et al. (2016) also acknowledged NOx contribution from the fire itself was possible, though focused on the plume's interaction with anthropogenic sources. In that 2015 study, smoke subsided across the eastern Midwest and northern Mid-Atlantic and took over 24 hours of aging before ozone above 70ppb was widespread across the region. This delay in ozone production while the airmass aged is consistent with previous studies such as Putero et al. (2014) which observed the largest increases in ozone from fires five days (120 hours) after the initial pollutants were emitted from the fire (Figure 9). This observation was also consistent with the behavior of the smoke plume in the May 2016 case. While sufficient amounts of NOx and VOCs were generated by the Fort McMurrary fire in early and mid-May of 2016 for ozone production, as the plume aged and mixed with anthropogenic NOx (albeit the lowest NOx on record) across the Midwest and Great Lakes of the US, ozone concentrations were augmented to and above levels exceeding the NAAQS not possible without the smoke.

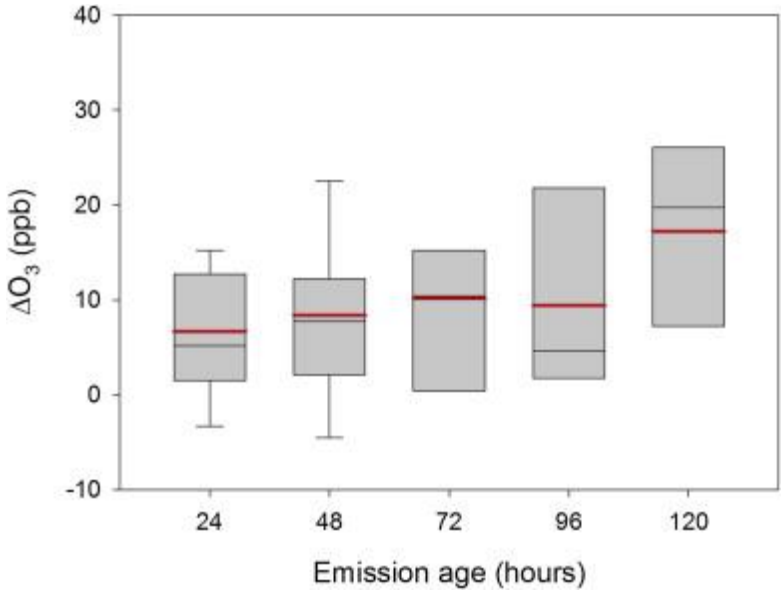


Figure 9. Ozone enhancement with smoke plume age. (from Putero et al. (2014), Figure 7)

The main smoke plume and ozone precursors of interest connected to Maryland's ozone exceedances on May 25 and 26, 2016 dispersed southward into the northern plains and Midwest of the US beginning on May 20-21. Across these areas, which were upstream of Maryland, daily ozone concentrations increased with the temperature, creating a photochemically aged and modified (dirty) airmass. The main smoke influence on ozone concentrations in Maryland was accomplished within this photochemically aged airmass upstream, which was then transported in to the state. Ozone was elevated across Maryland beginning on May 24 as the modified airmass transport began when winds turned to the northwest, though exceedances of the NAAQS associated with the smoky airmass did not occur until May 25 and 26. Thus, high ozone concentrations were transported into Maryland which, while similar in nature to, were not associated with a non-event-type transport pattern. The path, residency and meteorological setup of the smoke plume indicate a dispersing smoke plume conducive to ozone transported from Canada, subsiding through the upper Midwest and Great Lakes, then moving into the northern Mid-Atlantic and Northeast states of the US. An additional ozone exceedance at one monitor on May 27 and May 28 were also arguably attributable to lingering smoke influences, but the May 25 and 26 exceedances were undoubtedly influenced by smoke and unequivocally exceptional.

While ozone exceedance days in Maryland are not unusual during the month of May, the magnitude and spatial scale of these particular exceedance days were beyond contemporary norms. Meteorological conditions and emissions on May 23 – May 26, 2016 (when the majority of ozone exceedances occurred) were not sufficient to cause the large spatial scale and multi-day exceedance event without additional wildfire-related ozone precursor emissions. Historical comparisons during the month of May show ozone concentrations and the number of monitors exceeding the standard at these magnitudes are rare (reference Figure 5), and are even rarer considering massive emissions reductions evident during that time period across the entire eastern US. Thus, it is unlikely such a widespread area exceeding the standard would have occurred without additional supportive atmospheric chemistry provided by the wildfire smoke.

2.4.3. Meteorological Conditions Driving Smoke and Ozone Transport

2.4.3.1. Conceptual Model Overview

An amplified atmospheric pattern developed across the continental United States (CONUS) characterized by a digging trough along the Northwest US Coast which reinforced a central CONUS ridge of high pressure building northward in to the central plains of Canada from May 18-26, 2016 (Figure 10, #1 & 2). Ahead of the high amplitude west coast trough, a low amplitude upper-level weather disturbance moved across the interior CONUS on May 20-21. This disturbance and associated weak surface low developed from the lee of the Colorado Rockies to the lower Mississippi River Valley by the morning of May 20 and moved eastward, taking clouds and associated precipitation to the east coast by May 21. There the weak upper level shortwave intensified, closed-off, and became stationary, not progressing northeastward until May 24 and providing a three day period of unsettled or cloudy weather in Maryland and a trough-ridge-trough pattern in the upper levels across the CONUS (Figure 10, #3). The overall morphology of the atmosphere created an expansive surface high pressure area across the Midwest and Great Lakes of the US. At the same time, winds above the surface supported transport of the Fort McMurray smoke plume into these same areas

(Figure 10, #4). The subsidence (sinking motion) associated with surface the high pressure (the physical characteristic which gives high pressure systems sunny skies) brought the transported smoke towards the surface over the Midwest and Great Lakes. There the smoky airmass aged over several days. When the east coast disturbance moved northeast by May 24, west and northwest winds across the northeastern US transported the aged airmass into Maryland and other states across the northeast US leading to the aforementioned ozone exceedances on May 25 and 26, 2016 (Figure 10, #5).

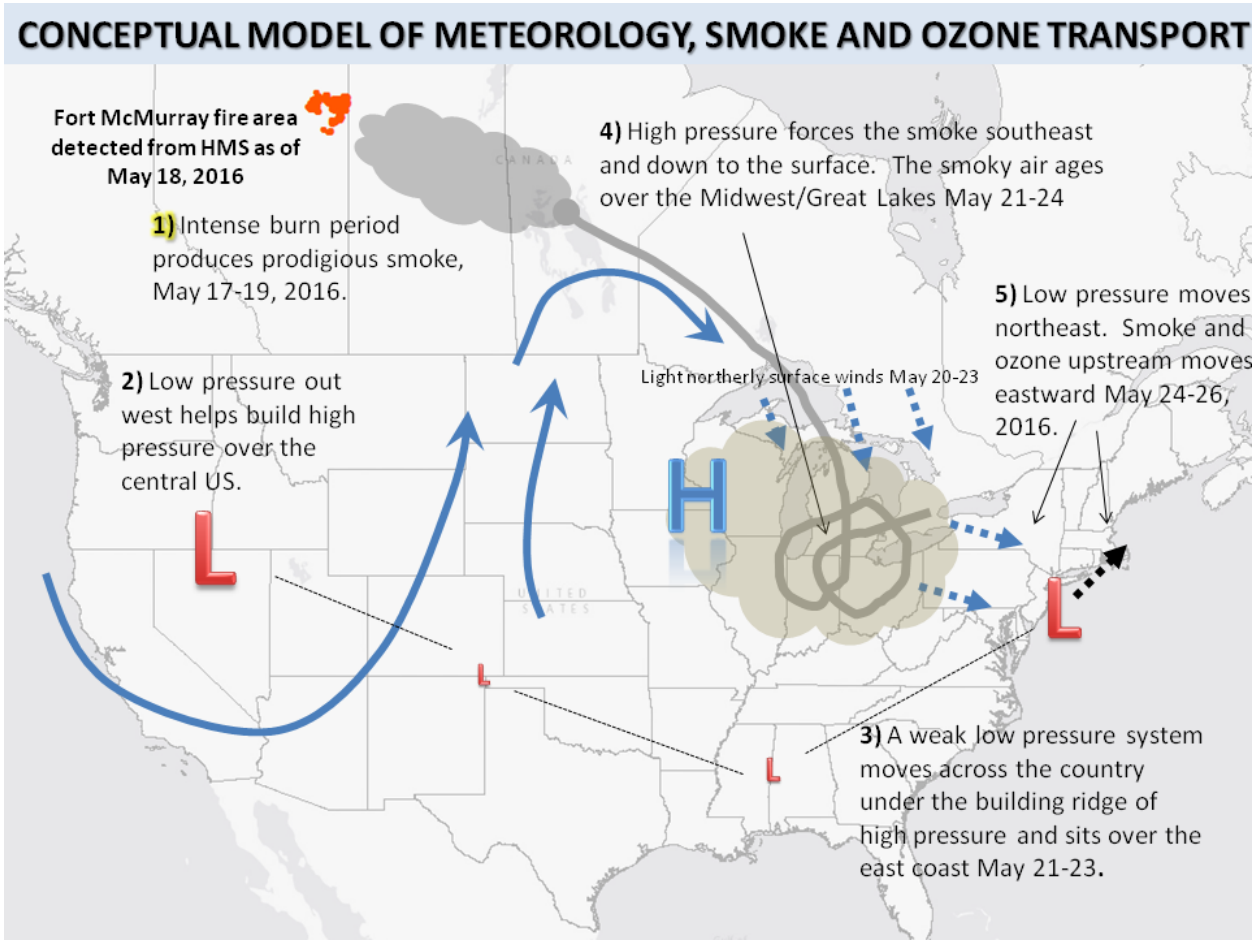


Figure 10. A simplified, illustrated, conceptual model of the May 25 and 26, 2016 wildfire influenced ozone event.

2.4.3.2. Upper Level Pattern Overview

The 850mb level (approximately 1500m above sea level) sits near the top of the planetary boundary layer, the atmospheric layer in which ozone pertinent to surface observations and human health develops. The 850mb height level can serve as a guide for the transport of pollutants. The morphology of this atmospheric level is given for May 21-26 in Figures 11-13. Initially the ridge of high pressure ("H" in the figures) was located over Minnesota and Wisconsin (Figure 11a). This allowed transport from southern Canada into the upper Midwest and Great Lakes region as the aloft winds at 850mb rotated clockwise around the ridge and

turned southward. Ridges of high pressure are associated with subsidence (sinking vertical motions) that brings air towards the surface. Air which resides or subsides under the ridge tends to remain under the ridge since near-surface winds under the ridge are generally weak. This leads to airmass persistence beneath the ridge, which occurred over the upper Midwest at this time. Over Maryland at the same time, an area of low pressure deepened (intensified) once it reached the coast on May 22 (Figure 11b). This brought clouds and unsettled weather, along with easterly turning to north-northeasterly airmass transport, all of which was unfavorable for ozone production, through May 23.

The transport pattern remained relatively persistent on May 23 as it had on May 21 and 22 (Figure 12a) but began to break down and become transitory (changing) by May 24 (Figure 12b). The ridge of high pressure over the Midwest and Great Lakes slowly moved eastward to reside over the Illinois, Indiana, Michigan and Ohio region by May 23. There, the airmass remained stuck beneath the ridge of high pressure. Over Maryland, the coastal low persisted, keeping Maryland in unsettled (cloudy, periods of rain) weather with clean northeasterly flow. On May 24 (Figure 12b) the coastal low began to lift northeastward. This changed the transport winds in Maryland from north and northeasterly to northwesterly which started to transport the smoky, modified airmass residing across the Midwest/Great Lakes into Maryland and the Mid Atlantic.

Transport winds across the northeastern CONUS were west and northwesterly on May 25 (Figure 13a). The airmass which started to move eastward on May 24 was now fully transported to the east coast on May 25 while the ridge of high pressure flattened (de-amplified/weakened) and moved eastward. As the ridge of high pressure continued to weaken and move east, it essentially phased with the Bermuda High (a semi-permanent high pressure area off the southeast coast of North America in the summer). As the ridge of high pressure and Bermuda High phased and the previous coastal low continued its trek northeast, the transport winds turned to the southwest across Maryland (Figure 13b). These winds began to remove the airmass that had settled across the area on May 25. However, the smoke was not removed before an additional exceedance on May 26.

2.4.3.3. Surface Pattern Overview

While transport winds provide information on the transport of airmasses and weather systems, surface conditions and features dictate whether an airmass may be capable of ozone production. The surface layer (ground level) is also the layer where ozone monitors and humans reside making the layer paramount to understanding ozone morphology. A broad area of low pressure resided over the Mid-Atlantic states beginning on May 21 (Figure 14a) bringing unsettled weather to that area. At the same time, high pressure across the upper Mississippi River Valley brought fair weather to those areas. Light northerly winds from southern Canada were pushing in to the Great Lakes region (east of the High pressure center; red arrows). A weak cold front was also pushing south across this same area. Air behind cold fronts is characterized by subsidence (sinking motion) which is consistent with the features (high pressure) seen at 850mb (Figure 11a). By May 22 (Figure 14b), the cold front had lost its temperature gradient identity (removing it from the analysis over the Great Lakes in Figure 14b), though northerly winds and associated subsidence continued across the upper Midwest and Great Lakes while light surface winds existed across Iowa, Illinois, and

Missouri under the center of high pressure. Maryland continued to receive northerly winds and cloudy, cooler conditions on May 22.

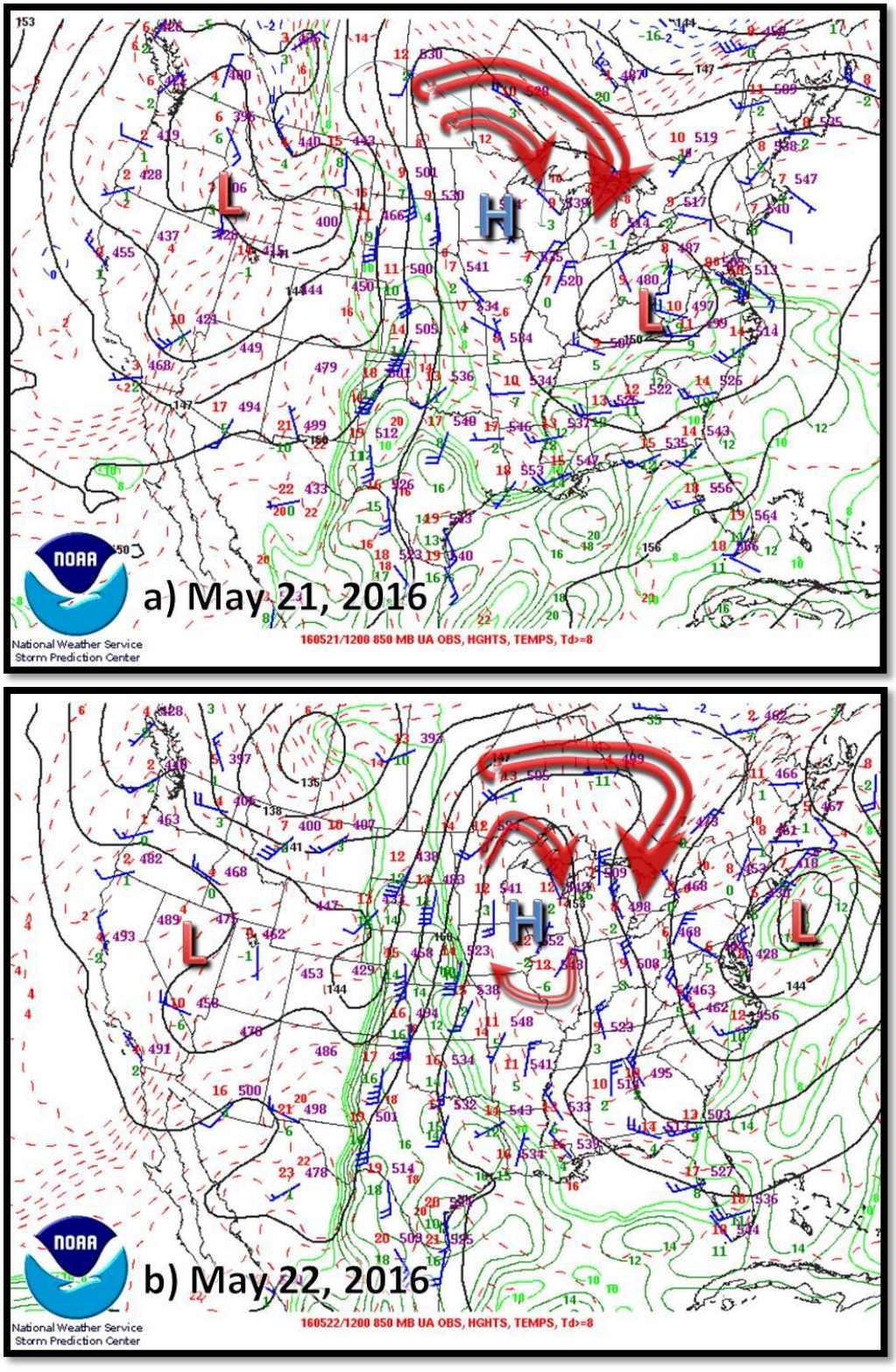


Figure 11. The 1200UTC 850mb pattern for the CONUS on a) May 21 and b) May 22, 2016.
Red arrows show the general transport pattern. Big letter "H" is high pressure, letter "L" is low pressure. Heights (black lines), temperatures (dashed red lines), dewpoint (green lines), and winds (blue barbs) are also analyzed. An omega-like pattern is apparent on May 22.

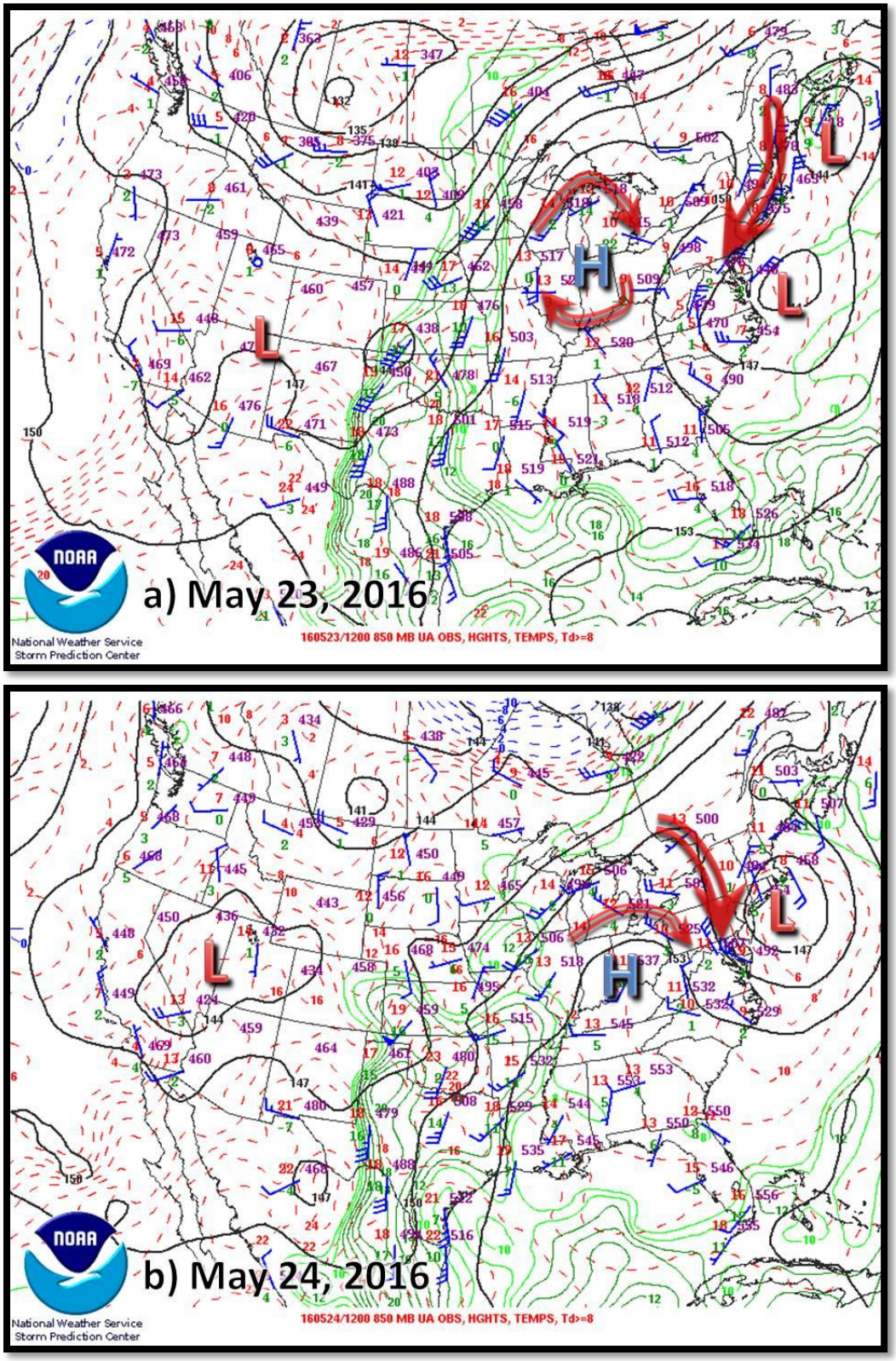


Figure 12. As in Figure 11, but for a) May 23 and b) May 24.

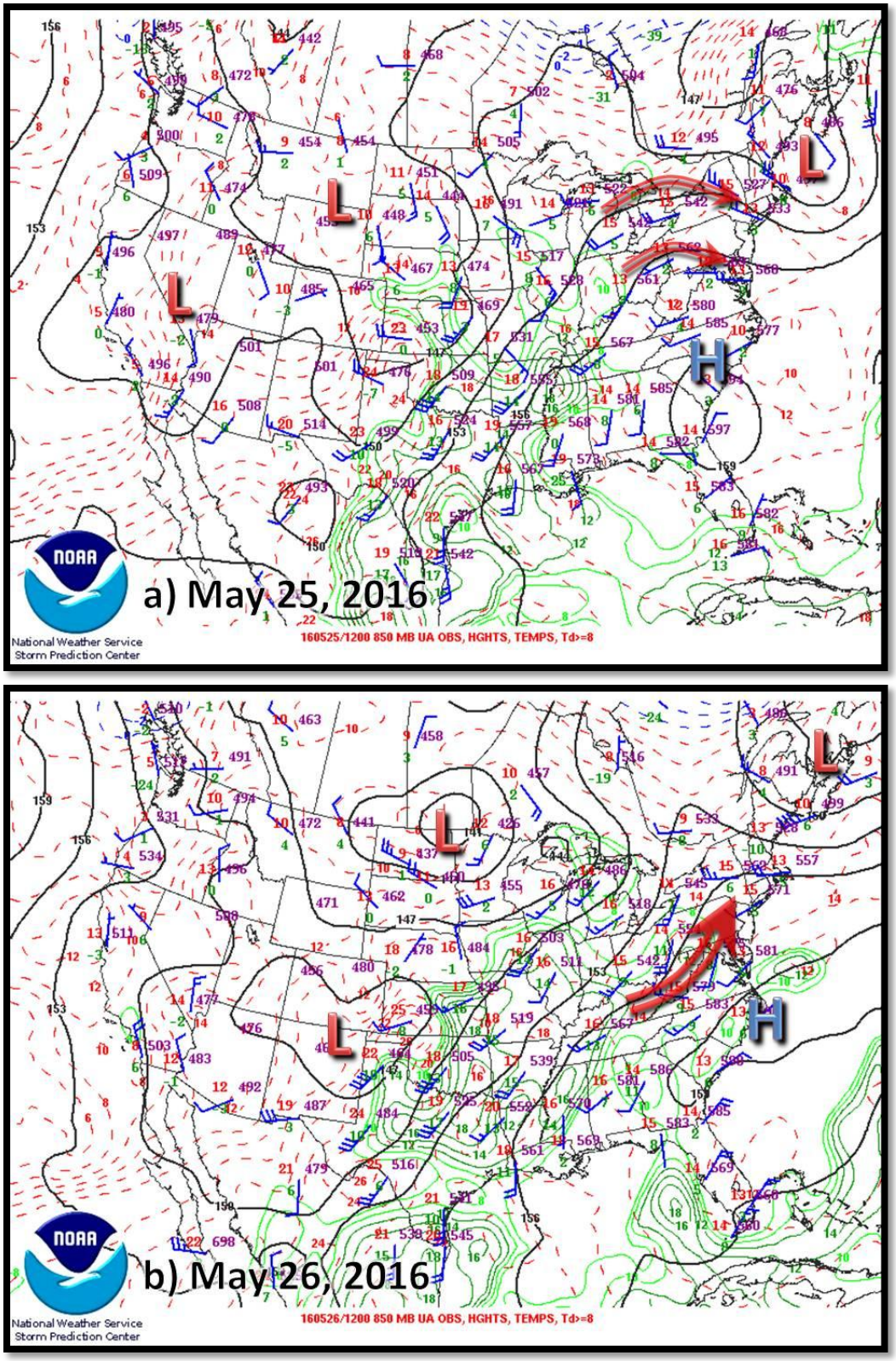


Figure 13.. As in Figure 11, but for a) May 25 and b) May 26.

By May 23, the center of high pressure over the Midwest slid eastward over Indiana and Ohio, while low pressure off the east coast continued to provide Maryland with unsettled and cooler conditions with northerly winds (Figure 15a). Light winds continued to characterize the surface conditions underneath the high pressure in the Midwest, with the airmass lingering and aging over these area. On May 24, the surface analysis showed the coastal low beginning to depart northeastward and that by 1800UTC (2pm EDT) on May 24 the surface winds in Maryland were turning to the northwest (Figure 15b). Consistent with the transport at 850mb (Figure 13a), the surface winds were beginning to move the airmass which was settled across the Midwest and Great Lakes eastward on May 24.

West and northwesterly winds at the surface continued on May 25 across the entire northeastern CONUS. This occurred as the area of surface high pressure began to "open up" and phase with the Bermuda high to the southeast while the coastal low continued to move northeast over Maine (Figure 16a). Maryland at this point was analyzed under the remaining weak surface high pressure, though it still received light west and northwesterly winds. By May 26 high pressure was centered southeast of Maryland off the coast of the US (i.e., the Bermuda High was now the dominant high pressure feature at the surface). This evolution turned the surface winds to the southwest across Maryland by May 26 (Figure 16b).

2.4.3.4. Temperature

Temperatures were above normal for the duration of the ozone exceedance event, however, above normal warmth in May is not necessarily ozone conducive nor do temperatures warmer than normal any longer mean ozone exceedances are likely. Similar to the observations of Dreessen et al. (2016), the smoke did not produce excessive ozone in May of 2016 until the smoky airmass warmed enough for ozone reactions to take place. The warmer temperatures in mid to late May 2016 were due to broad subsidence (which also mixes smoke downwards towards the surface) and warm air advection beneath the central CONUS ridge. The high temperature in Minneapolis, MN on May 21 was 9 °F warmer than normal, though only 80 °F (Table 3). At the height of the exceedance event in Indiana, the Indianapolis, Indiana airport high temperature climbed from 57 °F on May 17 to 82 °F on May 24 as the ridge of high pressure moved overhead. While 7 °F warmer than average, 82 °F is not particularly conducive to ozone formation without additional airmass support (proper photochemistry). Note that Indianapolis had an ozone exceedance with a modest surface temperature of only 78 °F on May 23. Detroit, MI at its ozone exceedance onset on May 23, had similar ozone production at an even cooler high temperature of 76 °F. Thus ozone production was intense despite low temperatures before reaching Maryland. On the days of the ozone exceedance in Maryland, maximum temperatures were 10 and 13 °F above average (Table 3). This general warming trend (i.e., temperatures incrementally greater than average as the airmass moved east) from west to east airmass indicated the airmass was modifying; polluted air is able to retain more heat.

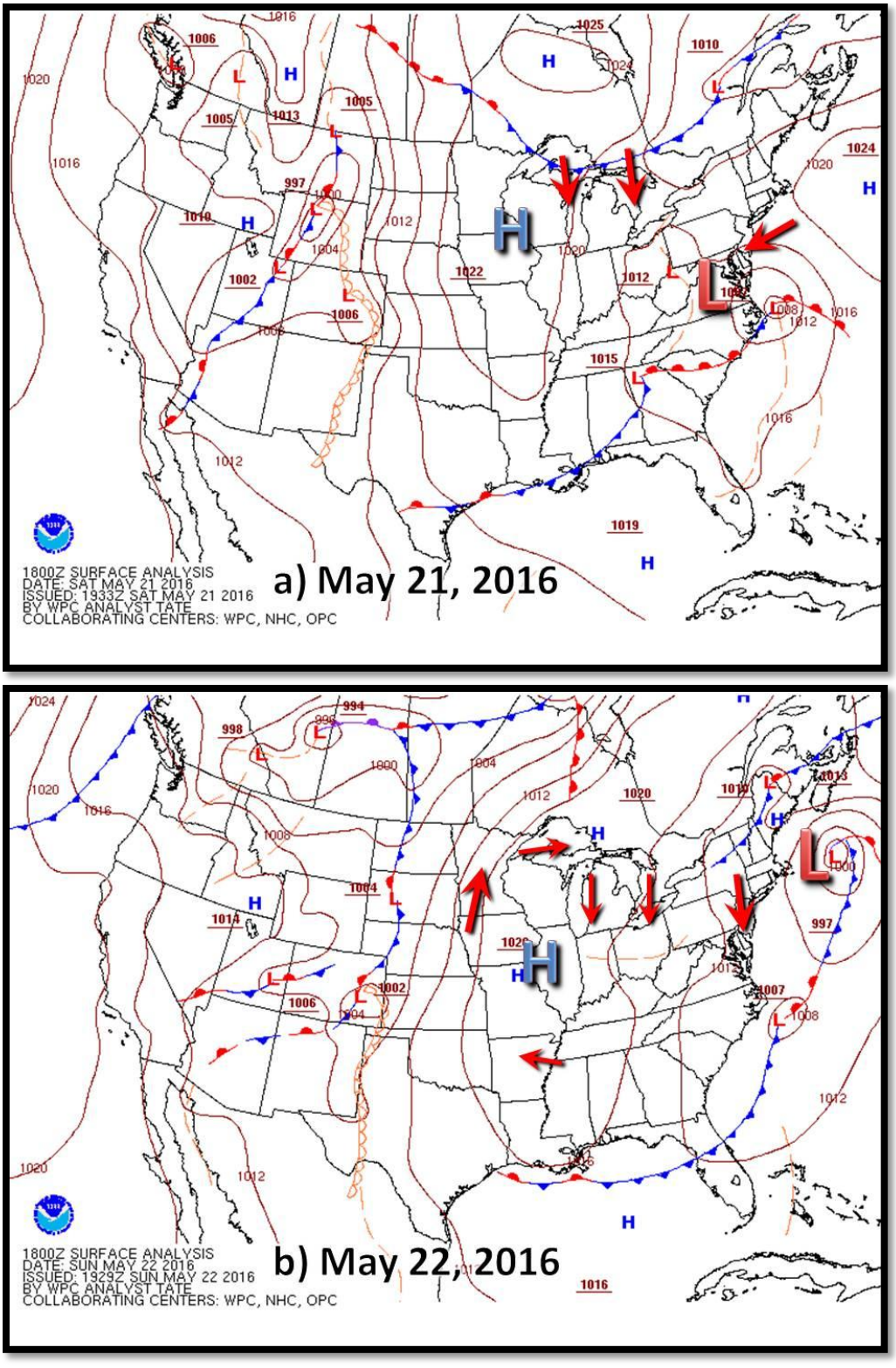


Figure 14. Surface analysis at 1800 UTC for a) May 21 and b) May 22, 2016.
Red arrows show the general pattern of surface winds. Big letter "H" is high pressure, letter "L" is low pressure. Isobars (brown lines) and fronts are also analyzed.

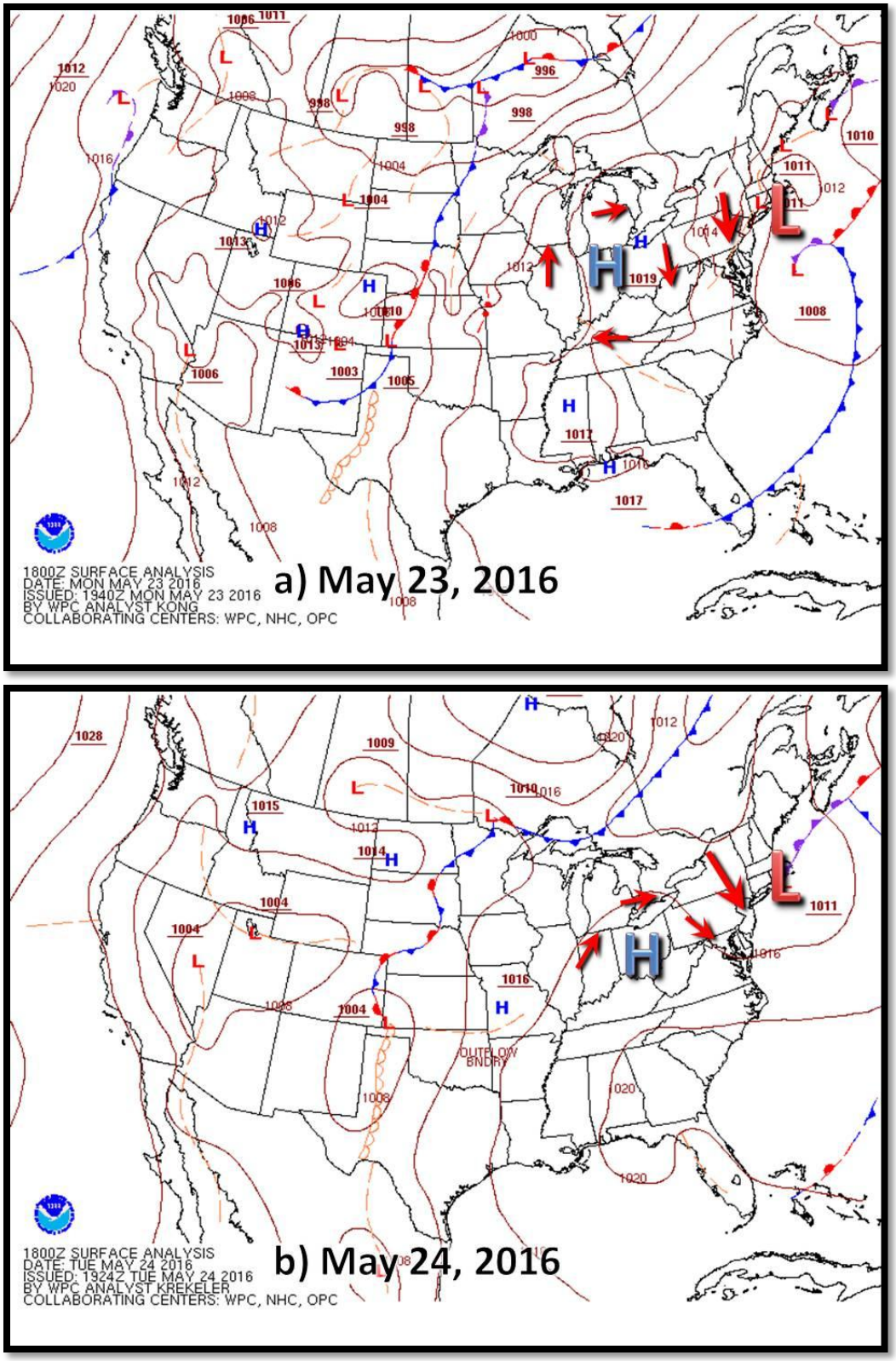


Figure 15. As in Figure 14, but for a) May 23 and b) May 24.

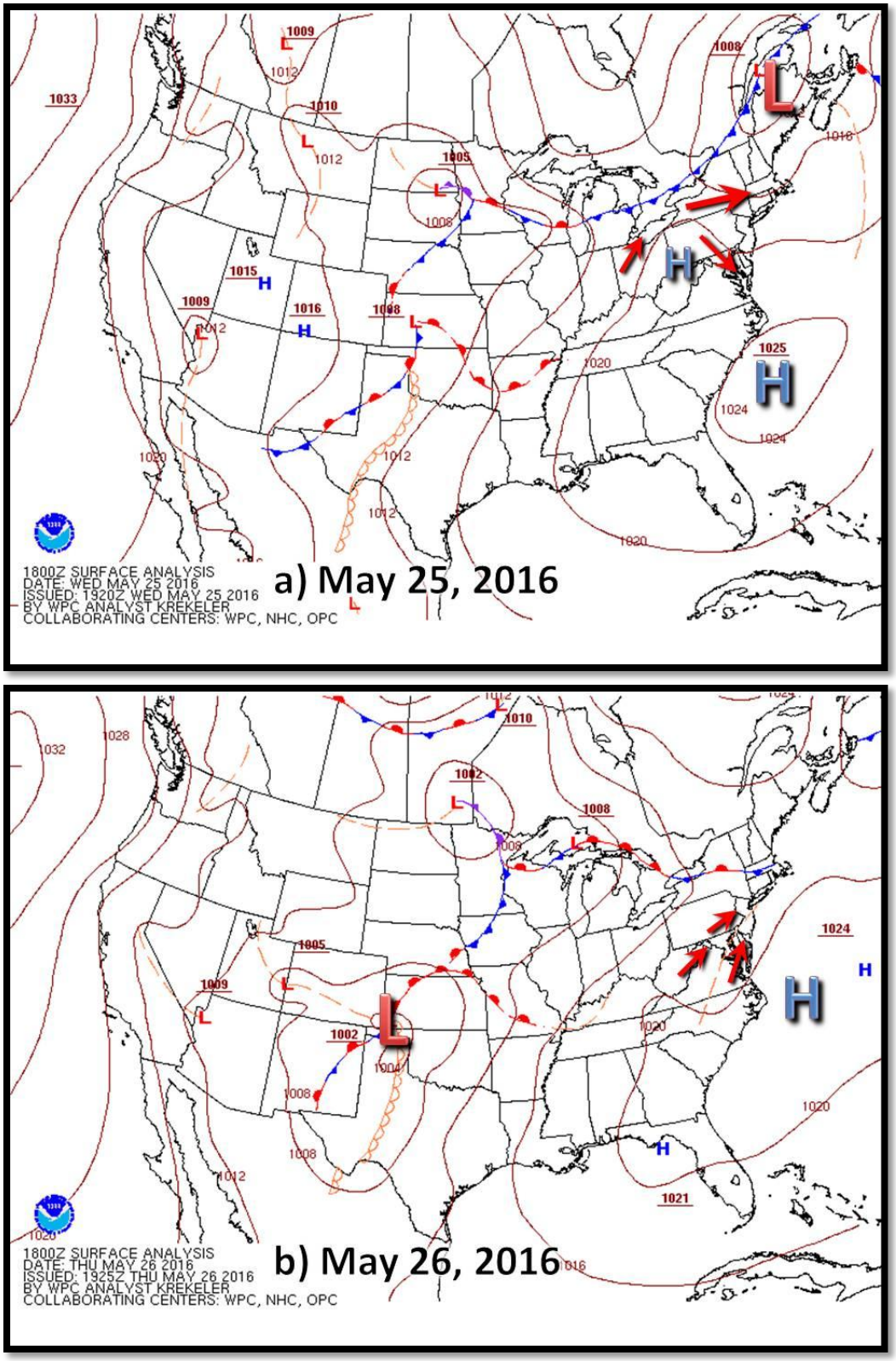


Figure 16. As in Figure 14, but for a) May 25 and b) May 26.

Table 3. Maximum daily temperature, average maximum daily temperature and departure from average.
Maximum daily temperature, average maximum daily temperature and departure from average (observation minus average) for various sites across the domain impacted by the smoke are provided for May 20 – May 28, 2016. All temperatures are in degrees Fahrenheit. Colored boxes show maximum daily 8-hour average ozone AQI at locations where nearby sites had ozone exceedances of 70ppb. The Columbus, OH area did not exceed during the event. However, other cities in Ohio (Cleveland, Cincinnati) did exceed on both May 24 and 25. Columbus was on the edge of the smoke plume both days; HMS never analyzed smoke over Columbus from May 23-28.

Date	20-May	21-May	22-May	23-May	24-May	25-May	26-May	27-May	28-May
Minneapolis, MN (°F)	76	80	84	84	86	76	81	70	68
Normal (°F)	71	71	71	71	72	72	72	73	73
Departure (°F)	5	9	13	13	14	4	9	-3	-5
Indianapolis, IN (°F)	68	73	81	78	82	84	77	85	83
Normal (°F)	74	74	75	75	75	76	76	76	76
Departure (°F)	-6	-1	6	3	7	8	1	9	7
Columbus, OH (°F)	72	60	72	76	80	80	80	88	86
Normal (°F)	74	74	75	75	75	75	76	76	76
Departure (°F)	-2	-14	-3	1	5	5	4	12	10
Detroit, MI (°F)	71	73	73	76	85	86	86	82	89
Normal (°F)	71	71	72	72	72	73	73	73	74
Departure (°F)	0	2	1	4	13	13	13	9	15
Rochester, NY (°F)	73	69	71	78	83	86	85	88	91
Normal (°F)	69	69	70	70	70	70	71	71	71
Departure (°F)	4	0	1	8	13	16	14	17	20
BWI, MD (°F)	75	62	60	75	82	86	90	90	88
Normal (°F)	75	75	76	76	76	76	77	77	77
Departure (°F)	0	-13	-16	-1	6	10	13	13	11
Meriden, CT (°F)	76	69	75	82	68	88	88	87	90
Normal (°F)	71	71	71	72	72	72	72	73	73
Departure (°F)	5	-2	4	10	-4	16	16	14	17

Though temperatures were warmer than normal in May of 2016, recent data has shown that warm temperatures are no longer sufficient for ozone exceedances in Maryland (Figure 17). For example, the once steady ratio of "hot days" to ozone exceedances (from 1980 – 2003) hit an all time high in 2016 with nearly twice as many hot days as ozone exceedances at the 70ppb standard. The number of hot days to the number of ozone exceedances has been exponentially increasing since 2003 indicating that temperature alone as a factor in ozone production is an increasingly unreliable predictor of ozone in Maryland. This emphasizes the importance of smoke in this case. Previously, greater probability of ozone NAAQS exceedance in Maryland was shown with higher temperatures (Lin et al., 2001) and historically, MDE has tracked Maryland's ozone exceedance days with temperatures equal to or exceeding 90°F (MDE, 2012; Warren, 2013). It is true that ozone precursors need warm temperatures to react to produce ozone. And, indeed, Maryland had above normal temperatures near the 90 °F threshold from May 25 – May 28 (Table 3). However, Maryland also had near-record warmth throughout the 2016 ozone season but recorded a very low number of exceedances. In fact, in a year with 48 days at or above 90°F, the greatest number of days in the last 17 years, there were only 26 exceedance days, which is the lowest ratio of ozone exceedances at the 70 ppb level to hot days ever. In August of 2016, a string of several days in the mid 90s produced no ozone exceedance days. This clearly shows that though ozone production occurs best under warm temperatures, warm temperatures do not indicate substantial ozone production will occur in Maryland.

The change in MD8AO magnitude and spatial coverage between May 25 and 26 and May 27 and 28 was driven by diminishing smoke influence. Only one monitor exceeded on May 27 and 28 as compared to 13 and 15 on May 25 and 26, respectively, with similar temperatures on all days. This illustrates that temperature was also not indicative of the scale of the ozone exceedance days in Maryland. By May 27, HMS no longer analyzed smoke across the region as the smoke-burdened airmass had largely been transported northward away from Maryland. Thus once the smoke-influenced airmass was primarily removed from the region, the constituents associated with ozone production were also removed on the regional scale. The temperature remained warm for only single monitor, isolated exceedances, but not for widespread ozone exceedances. Furthermore, there is no way to prove that the exceedances on May 27 and 28 were not also due to residual, smoke-influenced air. In fact, speciated particle data from May 27 suggests that smoke influences had not yet entirely left the area, implicating residual smoke was potentially the cause in at least another exceedance on May 27.

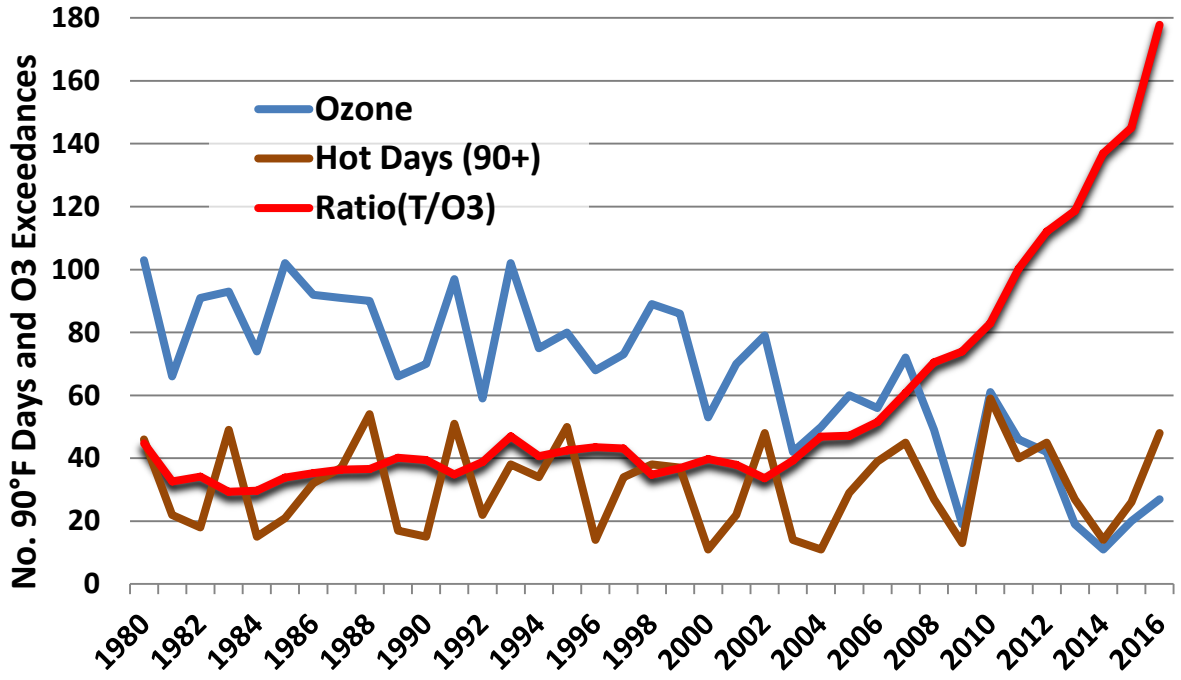


Figure 17. Ozone exceedance days to high temperature ratio.
A graph of the number of days with MD8AO in Maryland greater than 70ppb in a given ozone season (blue line), the number of days where the temperature at BWI airport reached at least 90°F in a given year (brown, thin line), and the five year moving average of the ratio of "hot days" to ozone exceedances multiplied by 100 for scale comparison (thick red, shadowed line) from 1980-2016. The dramatic increase in the ratio of hot days to ozone exceedances indicates the decreasing significance temperature has on ozone exceedance days in Maryland.

2.4.4. Smoke and Ozone Transport Overview

As a result of the weather pattern morphology, smoke and ozone produced due to the Fort McMurray, Alberta, Canada fire was transported to Maryland. Smoke from the Fort McMurray fire was already over the

northern plains on May 18 and 19, 2016 (Figure 18a,b). This smoke was ineffective at producing high ozone over the Midwest and Maryland due to the developing surface low on May 20 which moved across the middle of the CONUS. Weak northerly flow across the Mississippi River Valley and northern plains returned behind this surface low and HMS again analyzed smoke on May 20 across the far northern portion of the Great Plains (Figure 18c), and then farther south on May 21, across much of the Midwest (i.e., Missouri, Illinois, Indiana, Minnesota, Wisconsin, Michigan) as northerly flow continued (Figure 18d). Concurrent with the southward drift of smoke under the ridge, subsidence brought smoke and ozone pre-cursors to the surface. Additional smoke from fires across Mexico was observed on the western side of these images (Figure 18d, e, f) but is not considered part of the plume from Fort McMurray (located over the Midwest/Great Lakes) and is not considered further within the analysis. Subsidence and meandering of the Fort McMurray smoke plume under the ridge continued and on May 22 smoke was also analyzed over all of the Great Lakes states, Midwest and southeastward to the Carolinas (Figure 18e). The northern area of smoke expanded eastward on May 23, covering nearly the entire US east of the Mississippi River, including Maryland (Figure 18f). Those areas west of the coastal low (Michigan, Indiana, Illinois, Kentucky) saw their first ozone exceedance day due to the smoke plume. Despite smoke analyzed in parts of Maryland on May 23, no impact on ozone was observed, due to the influences of the low pressure system (Compare Figures 12a and 15a with Figure 18f). Instead, the smoke plume continued slowly eastward under the slow evolution of the upper-level pattern. Ozone production continued across the Midwest through May 24 where ozone exceedances expanded and intensified (Figure 18g) as compared to May 23 as the analyzed smoke plume started to move northeast around the ridge of high pressure centered over Ohio.

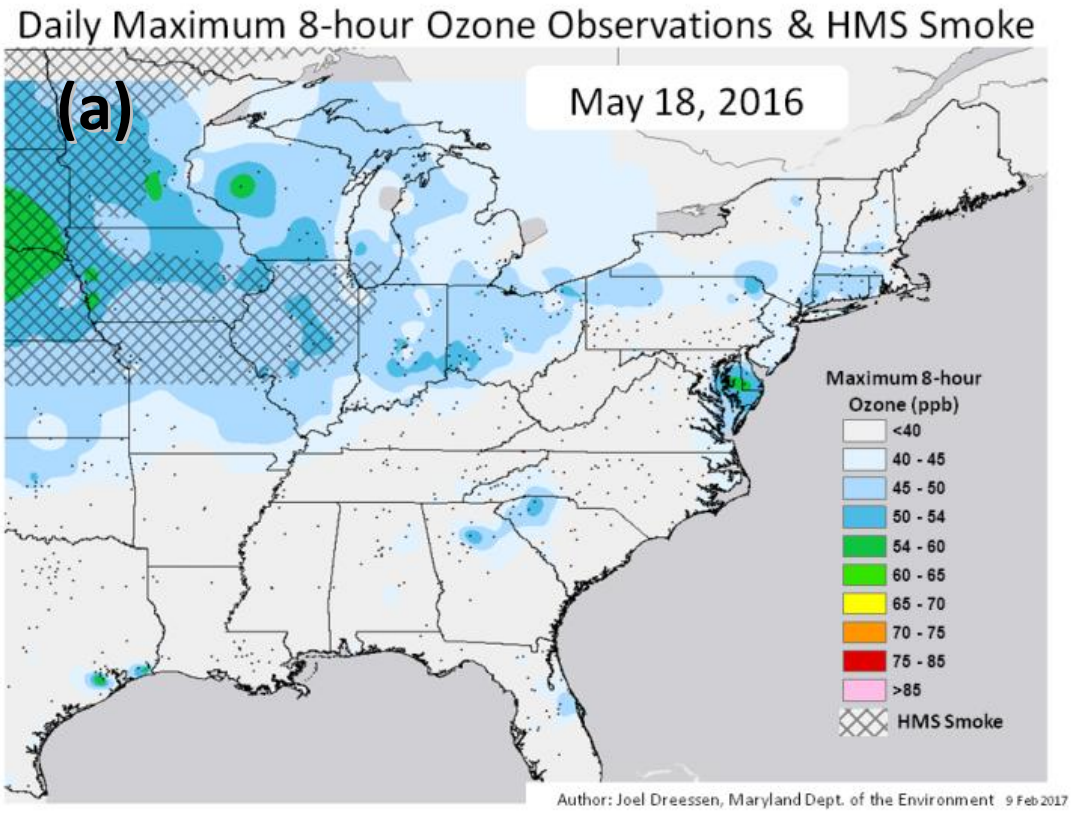
Maryland was on the southern fringe of the smoke-impacted air observed over the preceding days in the Midwest as the smoke and ozone was transported into the state on May 24 and 25, 2016. Surface high pressure centered over Ohio on May 23 fostered a continuing build-up of ozone, leading to a widespread area of high ozone on May 24 upstream of Maryland (Figure 18g). Transport from this region into Maryland began on May 24 but not early enough to lead to an MD8AO in exceedance of the NAAQS. On May 25 and 26, 2016, 13 and 15 Maryland monitors, respectively, exceeded 70ppb for their respective MD8AO due to the transport of the smoke-laden, photochemically aged airmass under the ridge of high pressure across the upper Midwest and Great Lakes. HMS analyzed smoke over Maryland and many of the areas with ozone NAAQS exceedances (Figure 18h). The smoky airmass lingered in Maryland on May 26, again lining up with the placement of the highest MD8AO (Figure 18i). As surface winds shifted to the southwest on this day, the orientation of the exceedances aligned with the I-95 corridor. No smoke was analyzed on May 27 or 28 over Maryland, and only single monitor ozone exceedance days occurred in Maryland. However, the highest MD8AO concentrations had moved northeast, the direction of surface and aloft (850mb) winds from May 26 to May 27, indicating the airmass laden with smoke and ozone had been transported northeastward out of Maryland. Ozone lingered on May 28, though the spatial extent of the exceedance across the entire northeast was further decreased due to further dispersion of smoke-impacted air regionally.

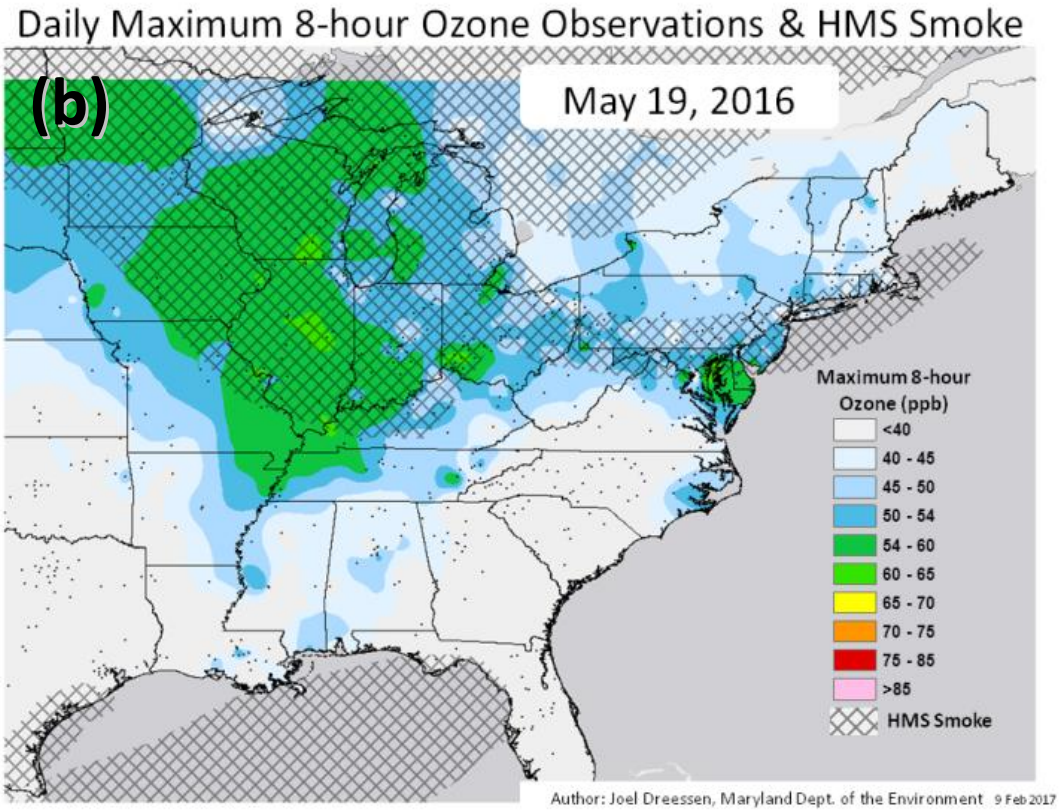
2.4.5. Smoke and Ozone Discussion and Analysis

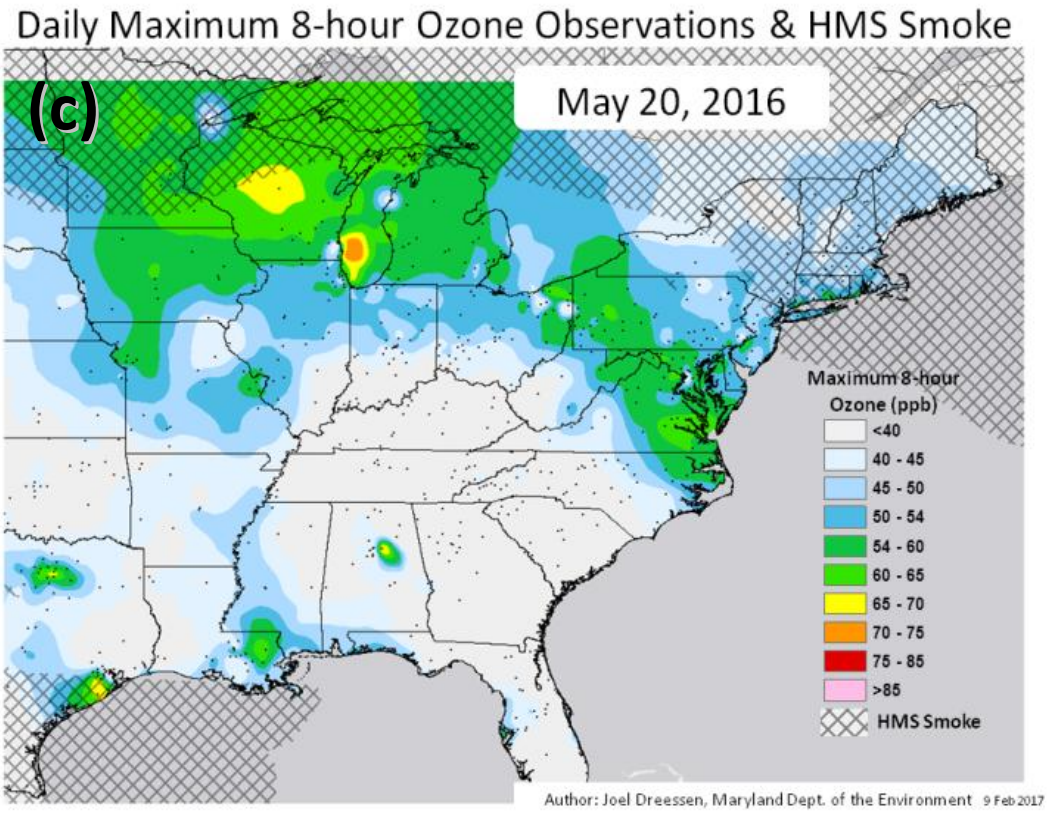
The spatial analysis of contoured MD8AO concentrations and HMS analyzed smoke showed the smoke transport from the Fort McMurray fire across the upper Midwest and Great Lakes into the northeast CONUS and Maryland matched the movement and development of high ozone concentrations (Figure 18). Initially on May 18 and 19, the highest ozone in the country was located in proximity to smoke across the upper Mississippi River Valley (Figure 18a,b). Then, behind a surface low which traversed eastward on May 20, these same areas saw rising ozone concentrations coinciding with HMS smoke concentrations on May 20 and 21, with an exceedance of the MD8AO in Minnesota and ozone concentrations climbing above 60ppb over a wide area (Figure 18c, d). Hourly fine particle observations (not shown), which act as a primary pollutant indicator for smoke at the surface, increased on the evening of May 20 and persisted in to May 22 around Minneapolis as another southward push of smoke began. By the evening of May 21, hourly particle concentrations well in to the teens and reaching towards 30 $\mu g/m^3$ were observed from Indiana, to Michigan and lower Ontario, Canada as well. These indicate that the smoke plume had reached the surface. Speciation data from May 24 support this conclusion (shown later), showing wildfire species at the surface. Also supportive of this conclusion was the HMS spatial analysis of the smoke plume which coincided with the surface $PM_{2.5}$ increases on these days. These were the same areas where ozone was rising, further supporting the spatial correlation of smoke and ozone.

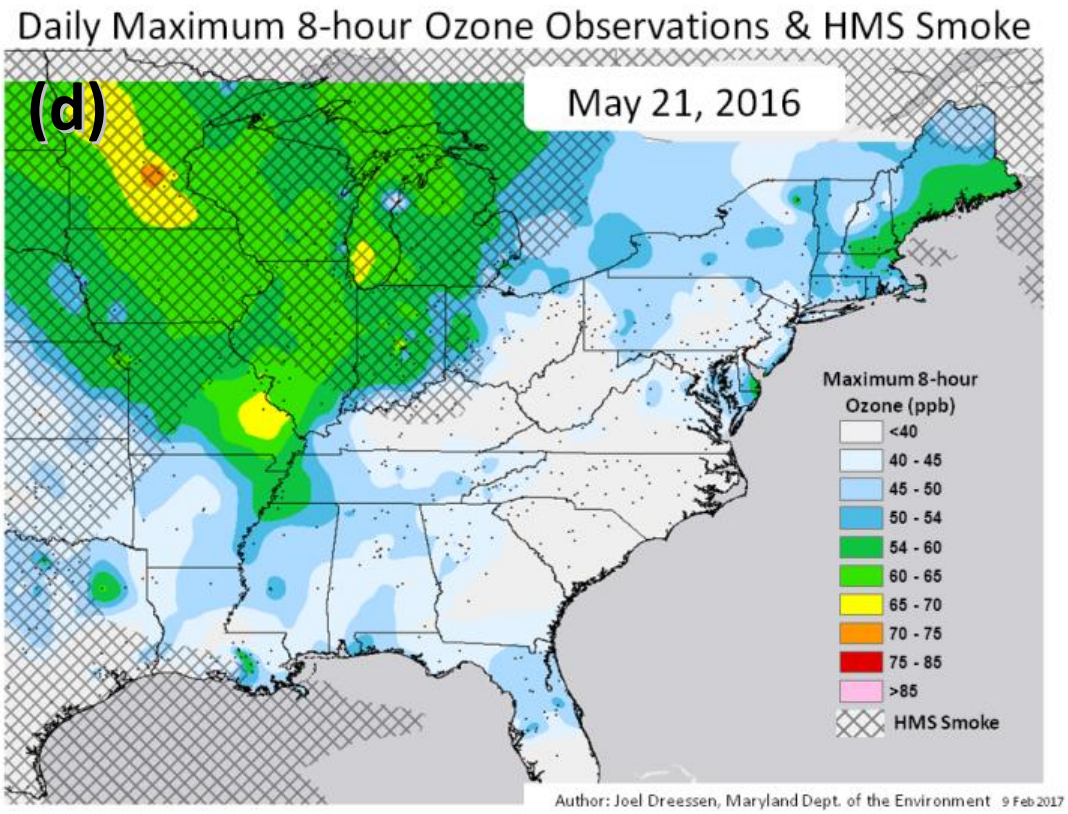
Smoke and ozone were analyzed farther south on May 22 (Figure 18e) and by May 23, HMS analyzed smoke perfectly overlapped with a broad and intensifying plume of ozone from the Gulf Coast through Michigan (Figure 18f). Isolated pockets of ozone exceedances over a broad area associated with this airmass were observed on May 23, primarily from the Missouri Boot Heel north-northeastward through the Great Lakes. Areas of the upper Midwest and Great Lakes had more intense ozone exceedances with greater coverage on May 24, expanding eastward in to New York and southern Canada where HMS tracked the northern portion of the smoke plume (Figure 18g).

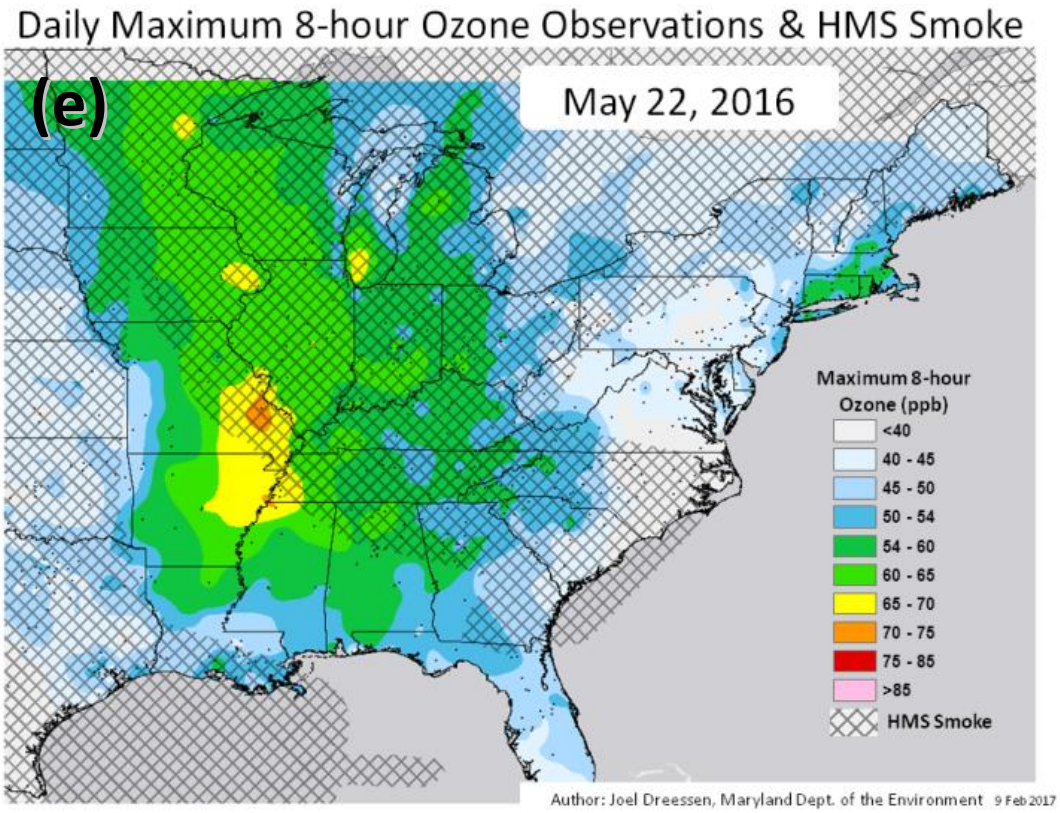
Both the HMS analyzed smoke and the highest MD8AO contours moved eastward between May 24 and May 25 with wide spread ozone exceedances from Connecticut to Maryland by the 25th (Figure 18h). Spatially significant was the persistence of ozone in Maryland with the persistence of the smoke plume analyzed over the eastern half of the state of Maryland on May 26 (Figure 18i). As claimed earlier, the smoke laden air mainly left the area on May 27 and 28 (Figure 18j and k) as HMS no longer analyzed smoke over the East Coast. An isolated exceedance persisted in Maryland, however, the magnitude and spatial coherence of the MD8AO across the northeast dissolved. Potentially enough residual smoke-affected air remained over Maryland to create exceedances downwind of urban plumes. Regardless, the reduced spatial scale of ozone coverage and magnitude on May 27 and 28 highlights the significance of the departure of the smoke. The movement of the smoke plume and ozone clearly coincide, indicating the smoke and ozone are connected and dependent in this case.

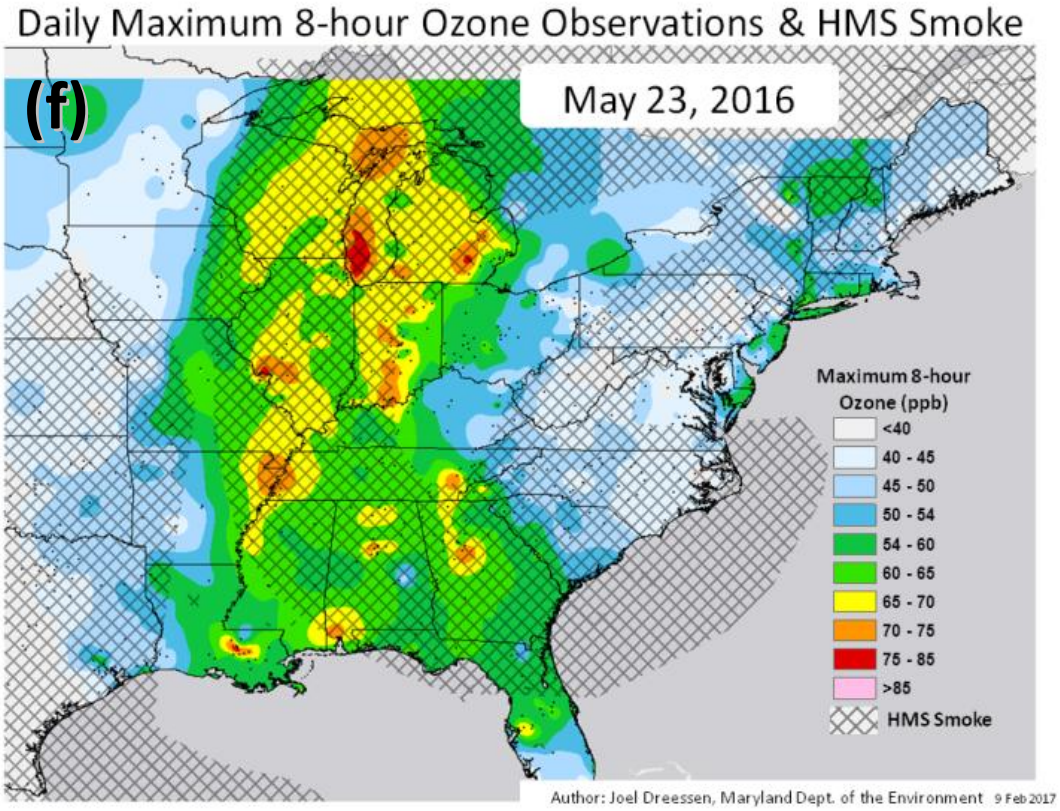

Daily Maximum 8-hour Ozone Observations & HMS Smoke
(a)
May 18, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017

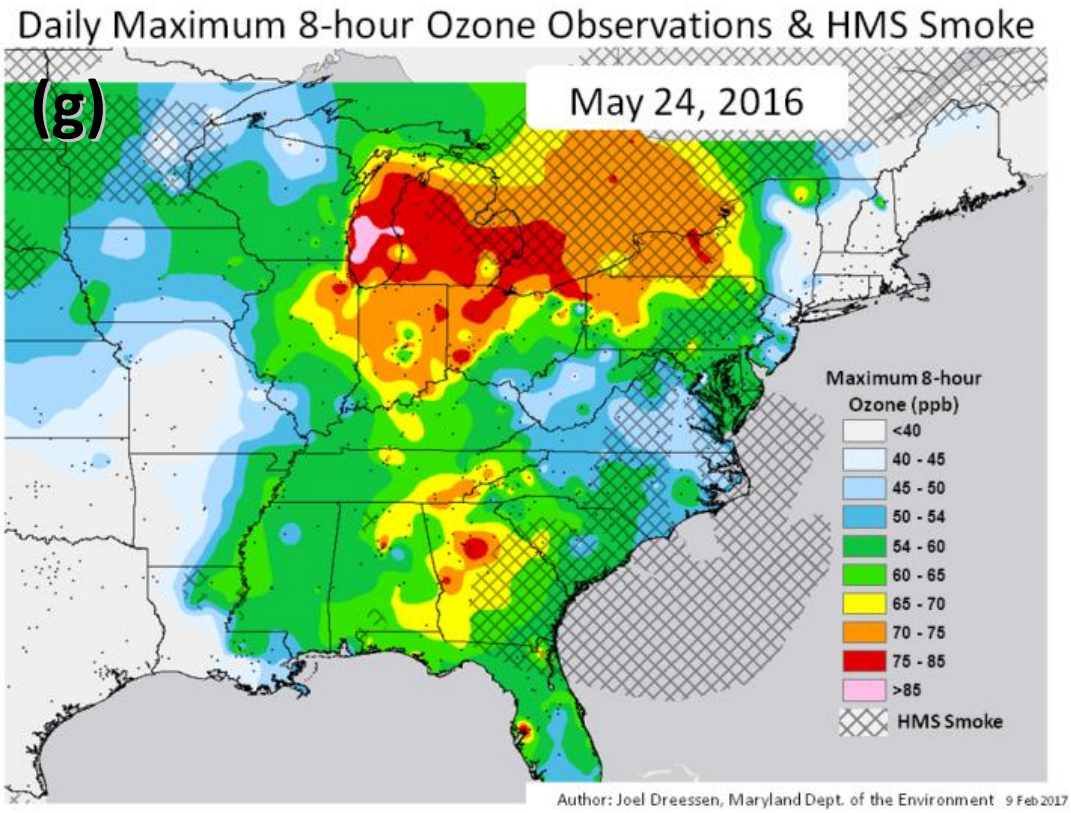

Daily Maximum 8-hour Ozone Observations & HMS Smoke
(b)
May 19, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017

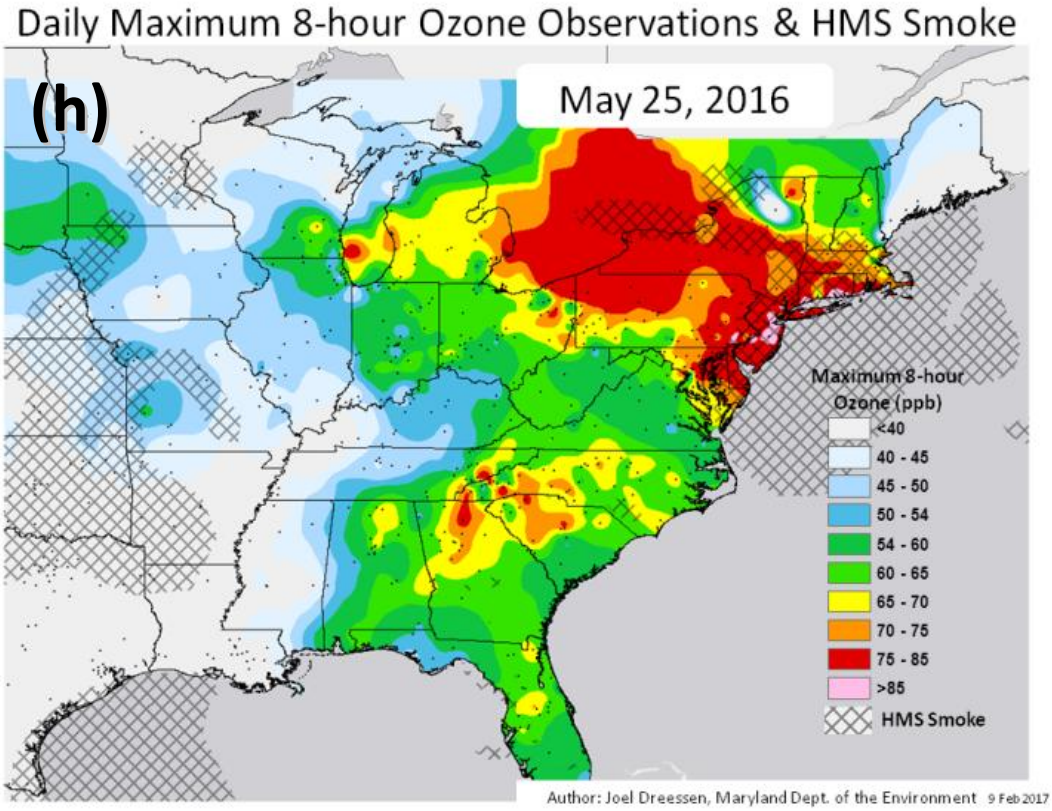

Daily Maximum 8-hour Ozone Observations & HMS Smoke
(c)
May 20, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017

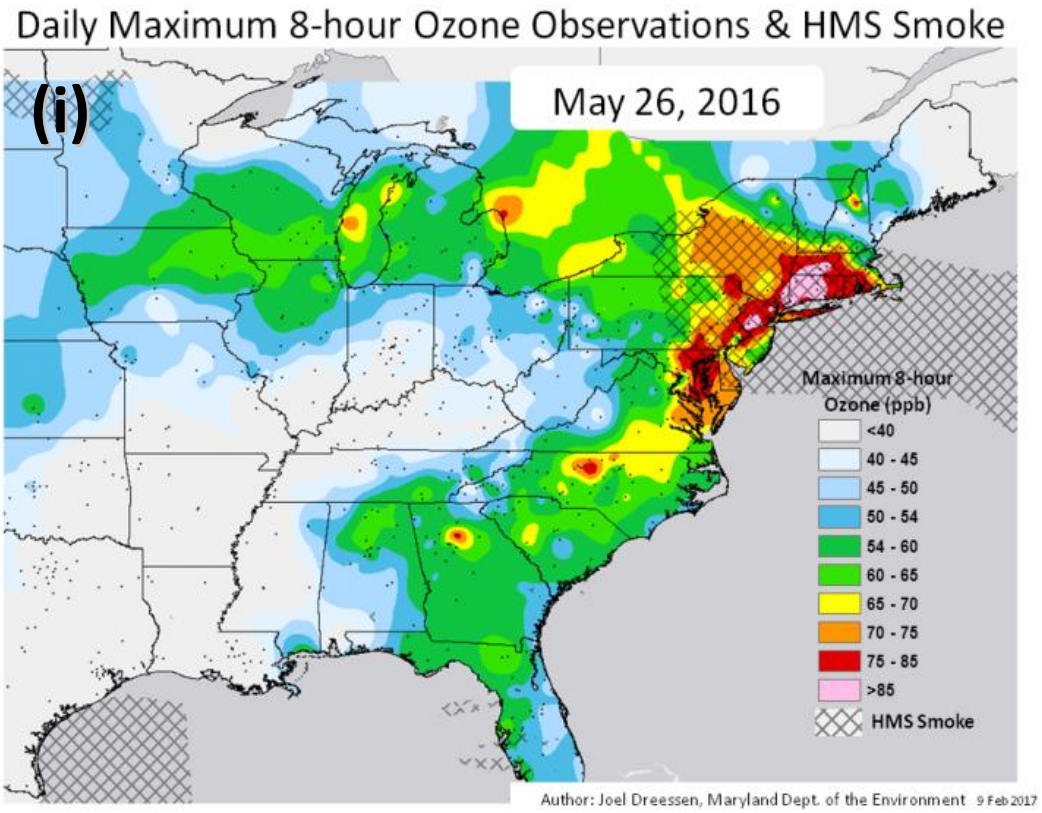

Daily Maximum 8-hour Ozone Observations & HMS Smoke
(d)
May 21, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017

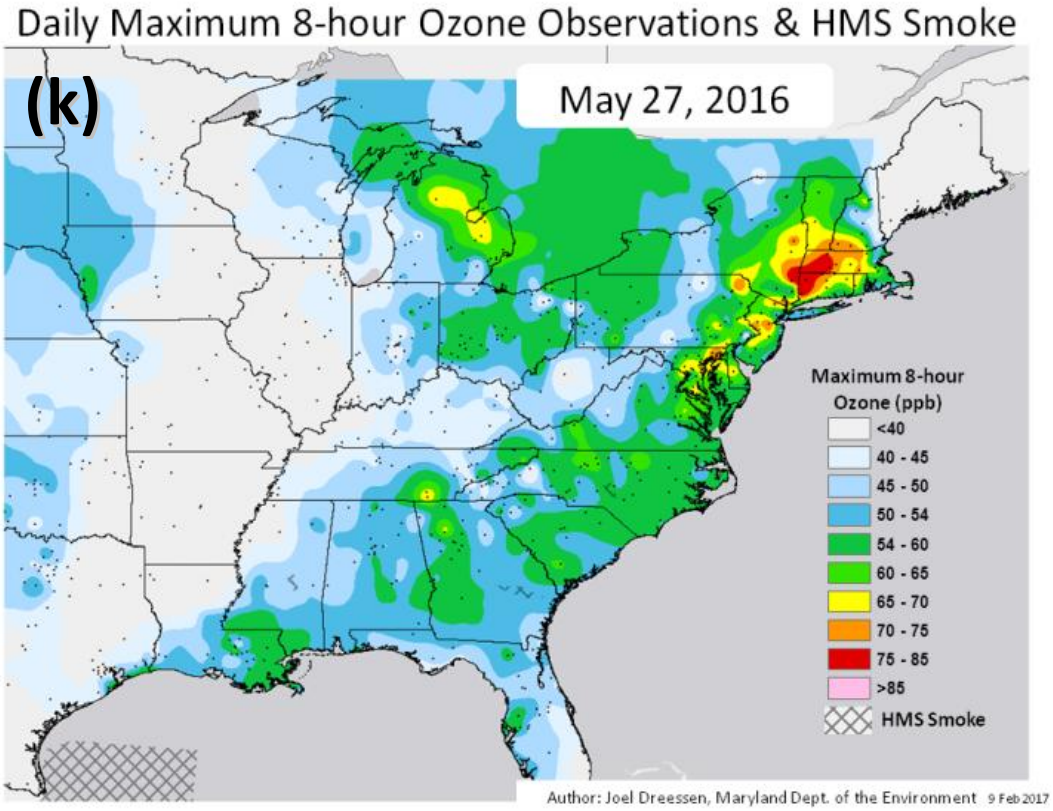

Daily Maximum 8-hour Ozone Observations & HMS Smoke
(e)
May 22, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017


Daily Maximum 8-hour Ozone Observations & HMS Smoke
(f)
May 23, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017


Daily Maximum 8-hour Ozone Observations & HMS Smoke
(g)
May 24, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017


Daily Maximum 8-hour Ozone Observations & HMS Smoke
(h)
May 25, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017


Daily Maximum 8-hour Ozone Observations & HMS Smoke
(i)
May 26, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017


Daily Maximum 8-hour Ozone Observations & HMS Smoke
(k)
May 27, 2016
Maximum 8-hour Ozone (ppb)
<40
40 - 45
45 - 50
50 - 54
54 - 60
60 - 65
65 - 70
70 - 75
75 - 85
>85
HMS Smoke
Author: Joel Dreessen, Maryland Dept. of the Environment 9 Feb 2017

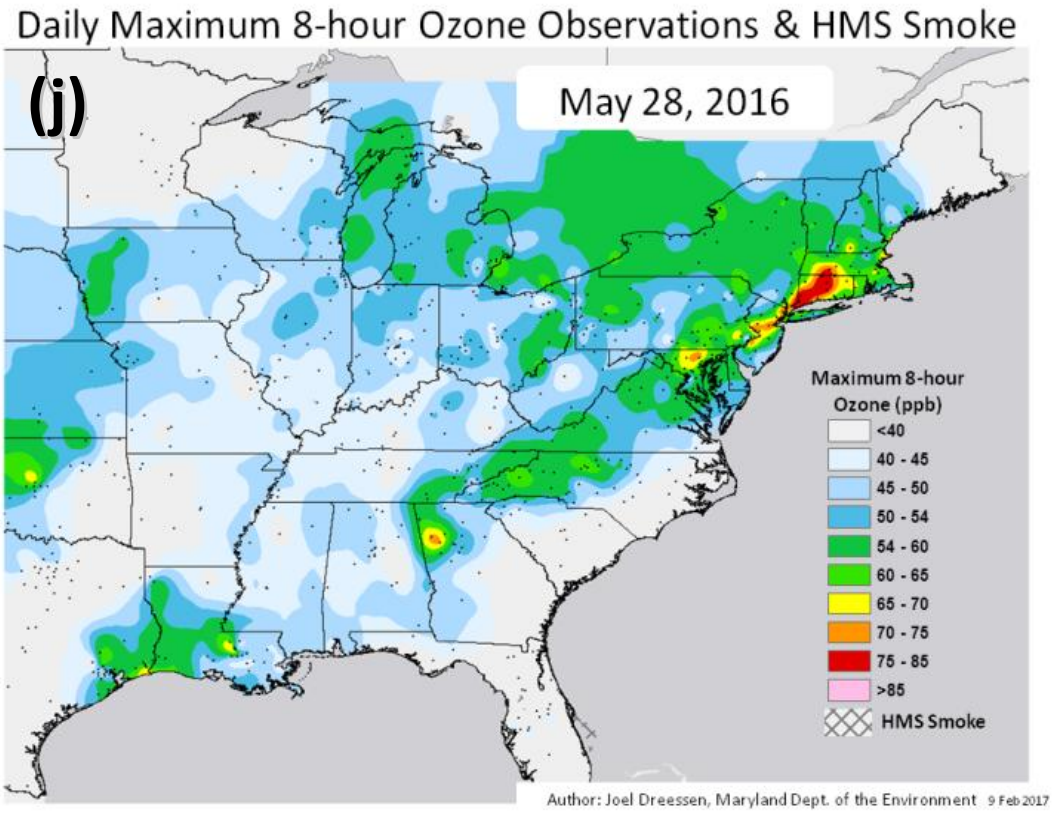


Figure 18. May 18-28 maximum daily 8-hour average ozone concentrations across the eastern CONUS.
Maximum daily 8-hour average ozone concentrations for the eastern CONUS (contoured colors) with Hazard Mapping System (HMS) analyzed smoke overlain (hatching) for May 18-28. Small black dots show the locations of ozone monitors from which the ozone isopleths were drawn. Analyzed smoke is closely associated with ozone plumes for each day up through May 26.

3. Clear Causal Relationship Between The Event and Monitored Ozone Concentrations

The case presented in this analysis illustrates an example of the impact of smoke on Maryland ozone concentrations via the transport of smoke-augmented, ozone-laden air into Maryland. MDE here presents necessary evidence to show the smoke event affected air quality in Maryland and clearly was associated with ozone concentrations beyond what otherwise is expected in the absence of smoke and that smoke caused the exceedance days. Comparisons to historical concentrations and a Q/d analysis (Tier 1 and 2 steps) are provided. While MDE believes these analyses alone show a causal relationship between the ozone and smoke, the complicated nature of the event may not clearly demonstrate a clear causal relationship. After conversations with EPA, it was deemed further analysis was necessary to further establish and demonstrate a clear causal relationship. Therefore, a weight of evidence (Tier 3) approach is used to build an irrefutable case that smoke transport was responsible for the ozone concentrations and the ozone exceedance days in Maryland.

3.1. Historical Concentrations

Scatter plots of MD8AO at Maryland monitors exceeding the 70 ppb NAAQS on May 25 and 26 showed the exceptional nature of the exceedances (Figures 19 - 34). All ozone data during the 2012-2016 ozone seasons (April 1 to September 30) were plotted for each monitor against that monitor's multi-season 99th percentile. However, recall that significant and sustained reductions in ozone precursors across the eastern US have occurred in the past 10 years. These reductions have been particularly evident in NOx. Consequently, this has lead to a noticeable decrease in ozone concentrations and exceedance days in the past three to four years. Five of lowest seasonal number of exceedance days occurred in the past 8 years, with four in the past four years, due to these NOx reductions. The May 20-31, 2016 period had the lowest late May emissions ever from 2010-2016 (Figures 4 and 5). Therefore, amplified MD8AO concentrations in 2016 represented substantially more ozone generated from available NOx than in 2012, when emissions were substantially higher. Since 2012 is within the previous five years of data that EPA requests for historical comparisons, MDE feels the data from 2012 raises the 99th percentile higher than what is otherwise now representative of Maryland's ozone. Thus MDE also offers two additional 99th percentiles to compare each monitor's MD8AO on May 25 and 26. These additional 99th percentiles are calculated using data which excludes 2012 (2013-2016) for the entire season, then another which compares only May from 2012-2016. MDE believes this increases the robustness of the historical comparison.

All monitors exceed a 99th percentile threshold on at least one of the two days and levels. Of the ozone data from the 16 monitors that MDE maintains as being influenced by an exceptional event, on May 25, 2016:

- Three (3) monitors met or exceeded the 99th percentile using all data from April 1 – September 30, 2012-2016 [Essex (240053001), Furley (245100054), Millington (240290002)].

- Nine (9) monitors met or exceeded the 99th percentile of the data when comparing only May ozone from 2012-2016 [Aldino (240259001), Beltsville CASTNET (240339991), Edgewood (240251001), Essex (240053001), Fair Hill (240150003), Furley (245100054), Millington (240290002), PG Eq Cntr (240338003), South Carroll (240130001)].

- Ten (10) monitors met or exceeded the 99th percentile of the data set when the 2012 ozone season was excluded [Aldino(240259001), Beltsville CASTNET (240339991), Essex (240053001), Fair Hill (240150003), Furley (245100054), Horn Point (240190004), HU-Beltsville (240330030), Millington (240290002), PG Eq Cntr (240338003), South Carroll (240130001)].

Of the 16 monitors that MDE is pursuing for exclusion, on May 26, 2016:

- Five (5) monitors met or exceeded the 99th percentile using all data from April 1 – September 30, 2012-2016 [Blackwater NWR (240199991), Essex (240053001), Furley (245100054), Padonia (240051007), South Carroll (240130001).

- Twelve (12) monitors met or exceeded the 99th percentile of the data when comparing only May ozone from 2012-2016 [Aldino (240259001), Blackwater NWR (240199991), Calvert (240090011), Edgewood (240251001), Essex (240053001), Furley (245100054), Glen Burnie (240031003), Horn Point (240190004), Millington (240290002), Padonia (240051007), South Carroll (240130001), S. Maryland (240170010)].

- Twelve (12) monitors met or exceeded the 99th percentile of the data set when the 2012 ozone season was excluded [Aldino (240259001), Blackwater NWR (240199991), Calvert (240090011), Edgewood (240251001), Essex (240053001), Furley (245100054), Horn Point (240190004), HU-Beltsville (240330030), Millington (240290002), Padonia (240051007), South Carroll (240130001), S. Maryland (240170010)].

All 16 monitors that MDE contends were influenced by an exceptional event exceeded a 99th percentile. Additionally, there were only three (3) instances where the MD8AO concentrations on May 25 or 26 were NOT one of the fourth highest observations of the 2016 season at that monitor. Those three observations are Fair Hill, May 26, which was the fifth highest of the season, though would become the fourth highest if MDE's July exceptional event demonstration is concurred, Glen Burnie on May 25 (sixth highest) and PG Eq Cntr on May 25 (fifth highest). PG Eq Cntr on May 25 would also become the fourth highest observation if the July exceptional event is concurred. It is safe to say the event caused one of the highest ozone concentraitons at all monitors which exceeded the standard (and even at those that did not – see Appendix B). The following scatter plots from all 16 monitors show the above data (Figures 19-34). Along with the 70ppb NAAQS, three additional lines show the 99th percentile for all ozone season data 2012-2016, ozone season data from 2013-2016, and only ozone in May, 2012-2016.

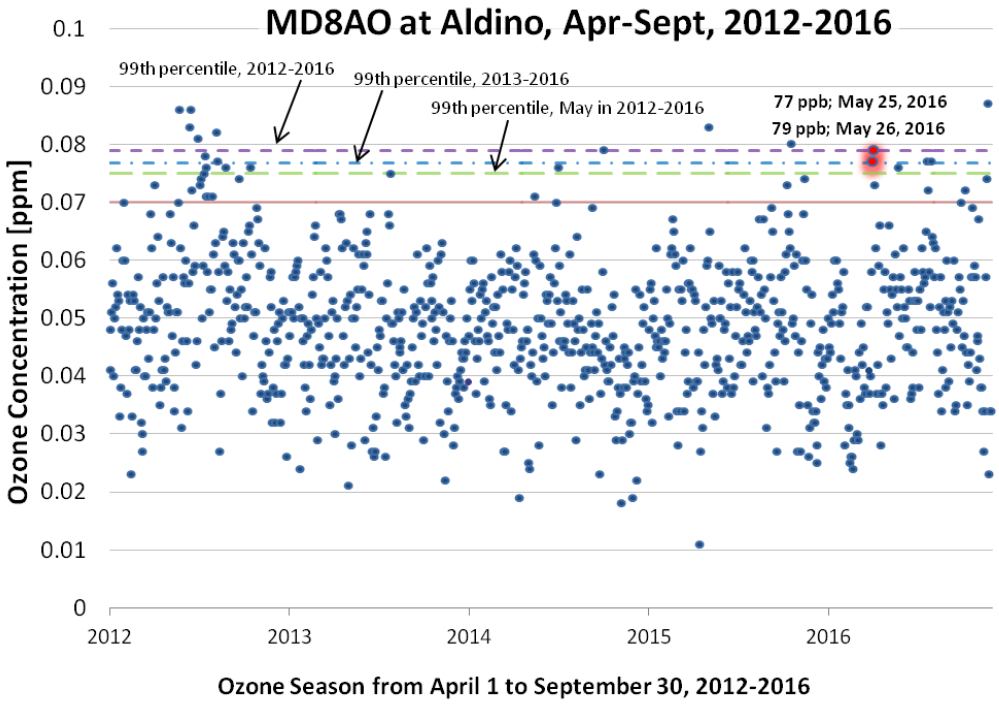


Figure 19. Scatterplot of Maximum Daily 8-hour Average Ozone (MD8AO) concentrations at Aldino (blue dots), April 1 – September 30, 2012-2016.
The days that exceeded the NAAQS on May 25 or 26 and for which MDE is seeking exclusion of the data are colored red. Textual annotations give the MD8AO for the red colored data point. Along with the NAAQS level (70ppb – red line), three 99th percentile lines are given to account for the changing NOx emissions and ozone levels in Maryland over the past 5-years. The 99th percentile for all ozone season data, 2012-2016, is given in dashed purple. All season data 2013-2016 is given in blue (dash-dot) while data only from May 2012-2016 is given in long-dashed green.

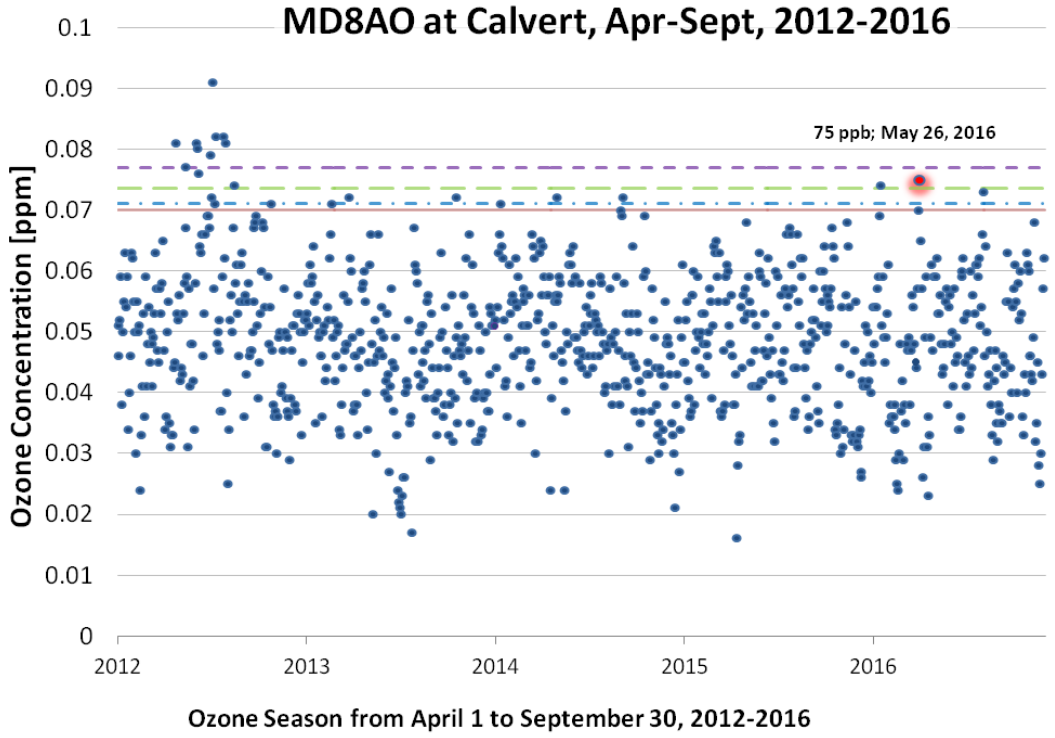


Figure 20. As in Figure 19 except for Calvert.

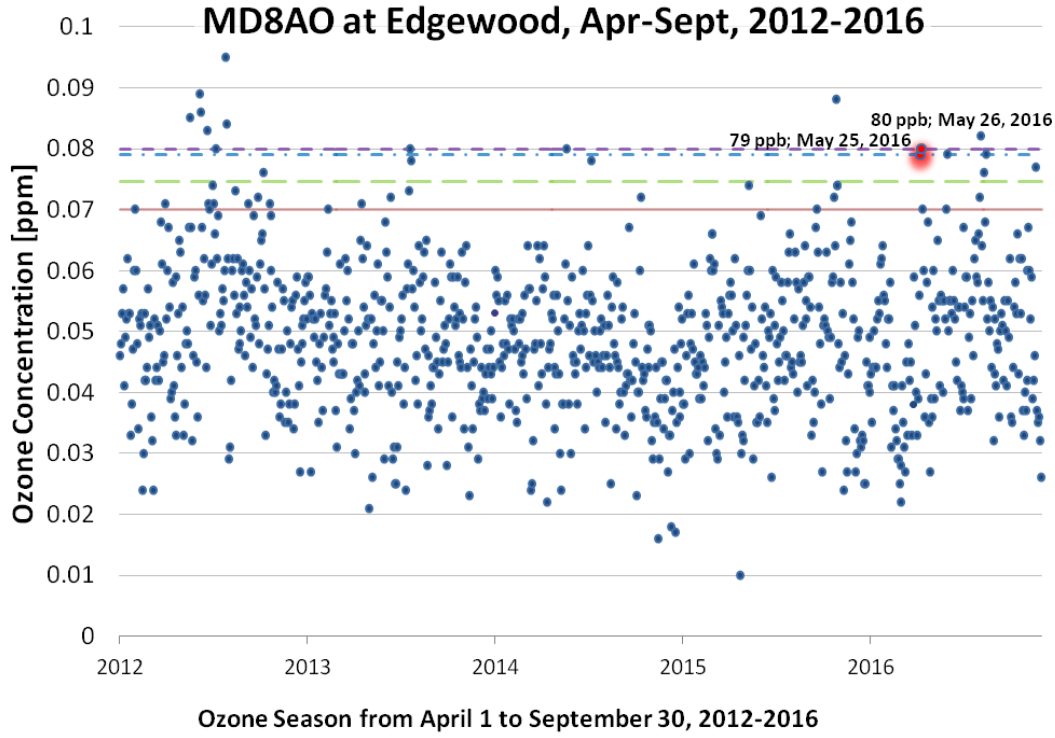


Figure 21. As in Figure 19 except for Edgewood.

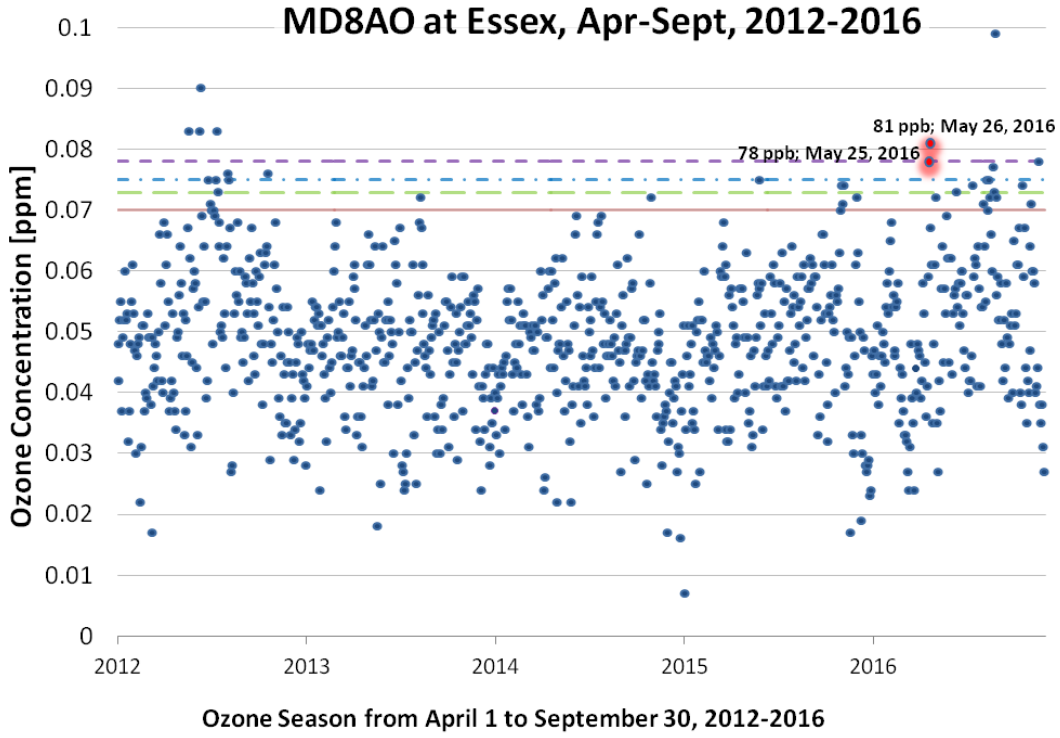


Figure 22. As in Figure 19 except for Essex.

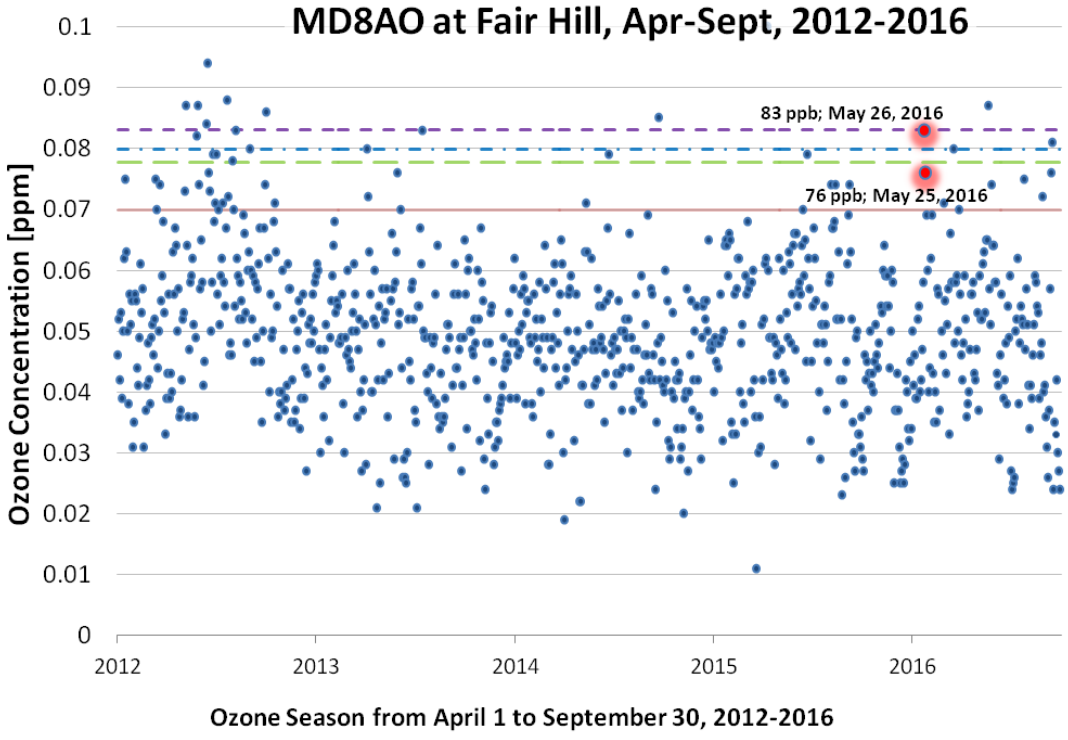


Figure 23. As in Figure 19 except for Fair Hill.

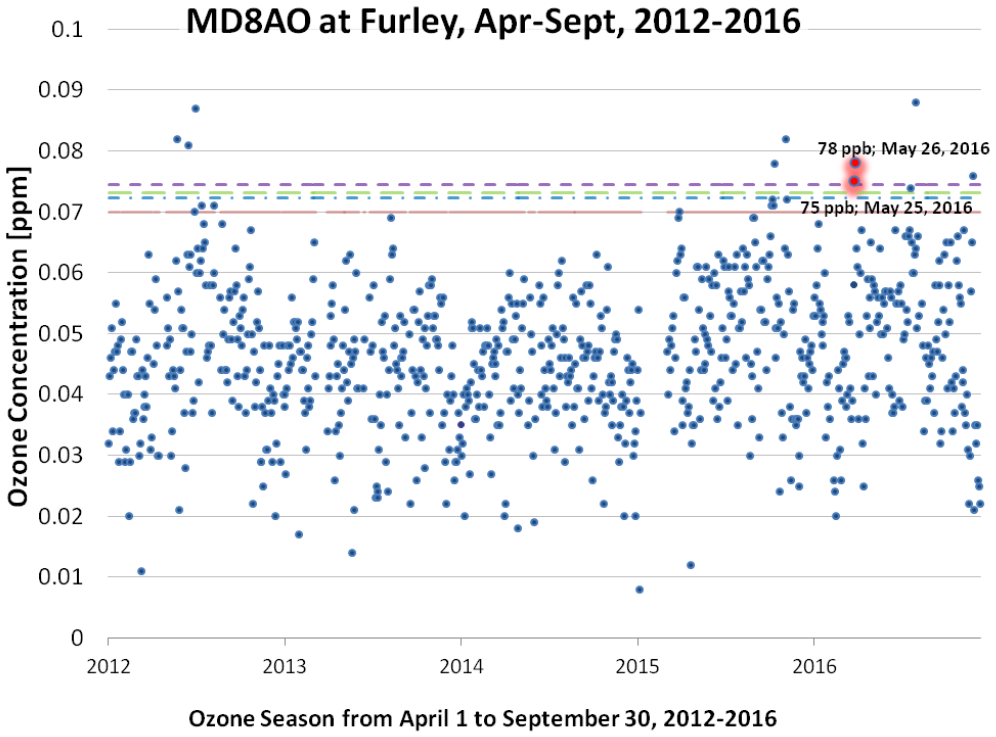


Figure 24. As in Figure 19 except for Furley.

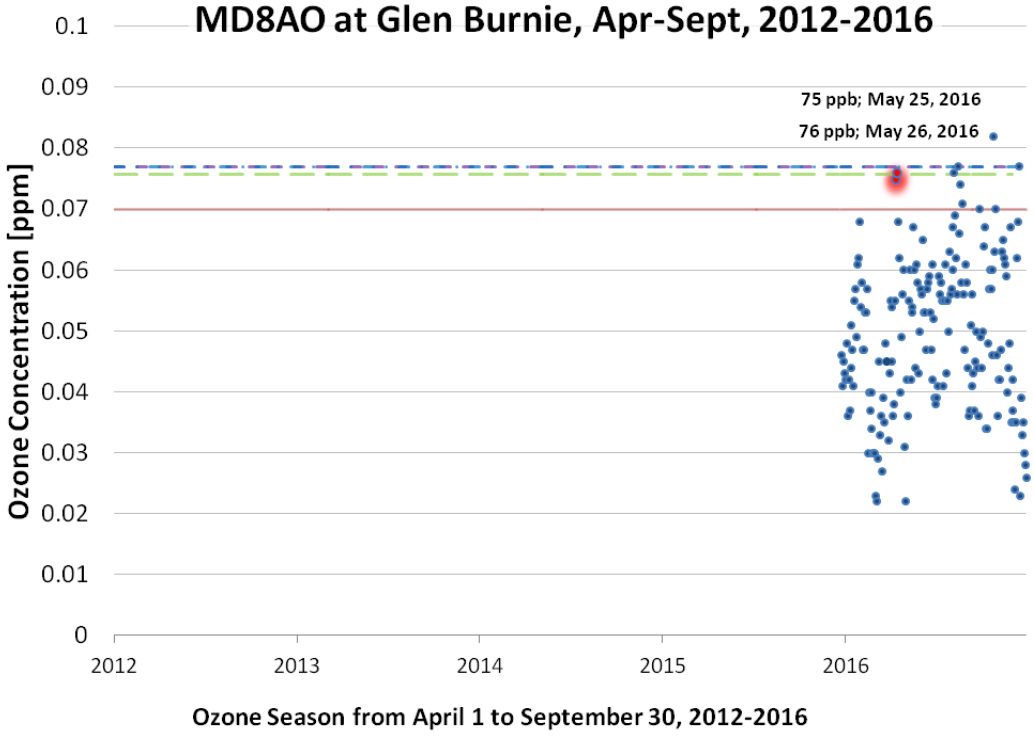


Figure 25. As in Figure 19 except for Glen Burnie. Glen Burnie became operational in 2016.

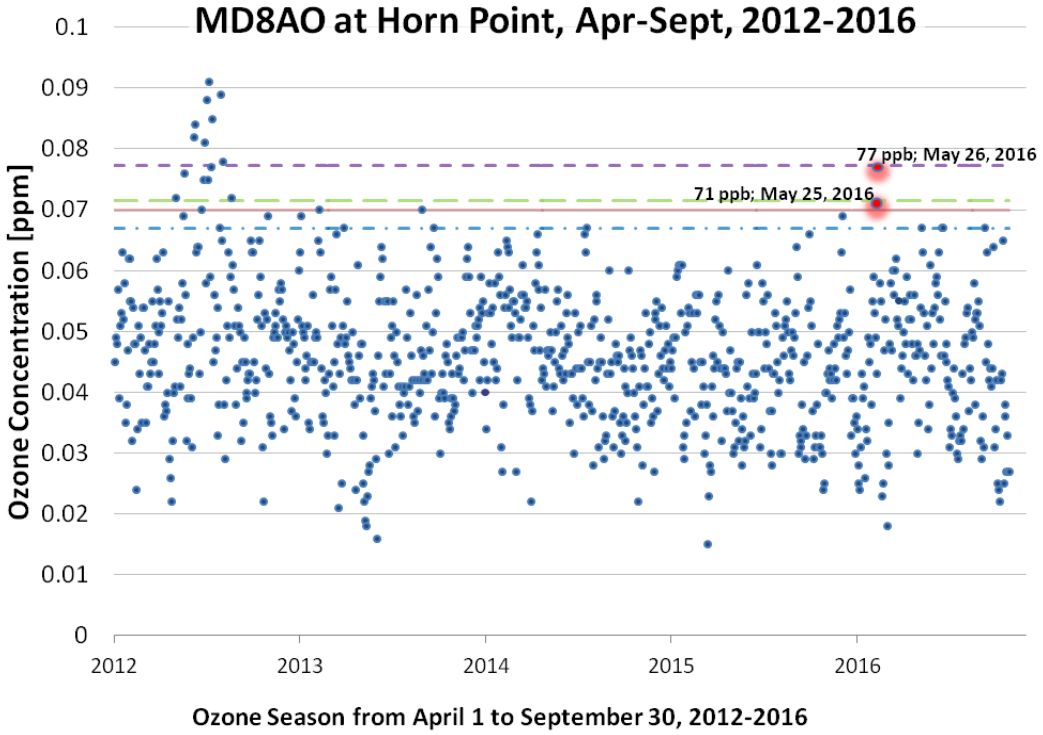


Figure 26. As in Figure 19 except for Horn Point.

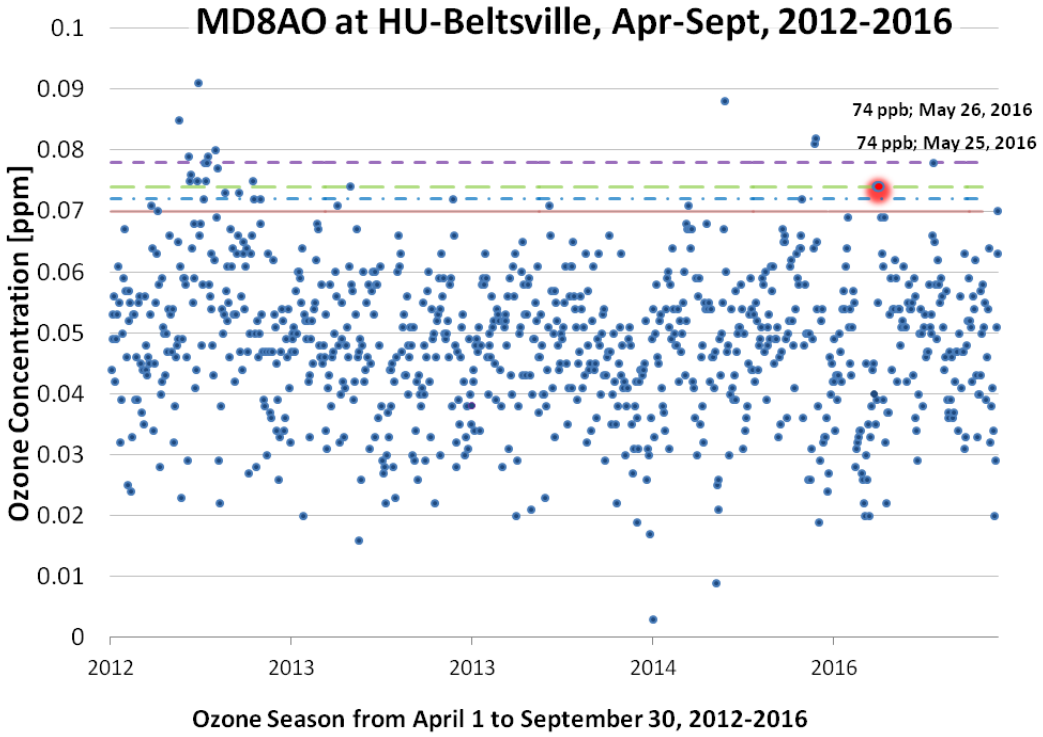


Figure 27. As in Figure 19 except for HU-Beltsville.

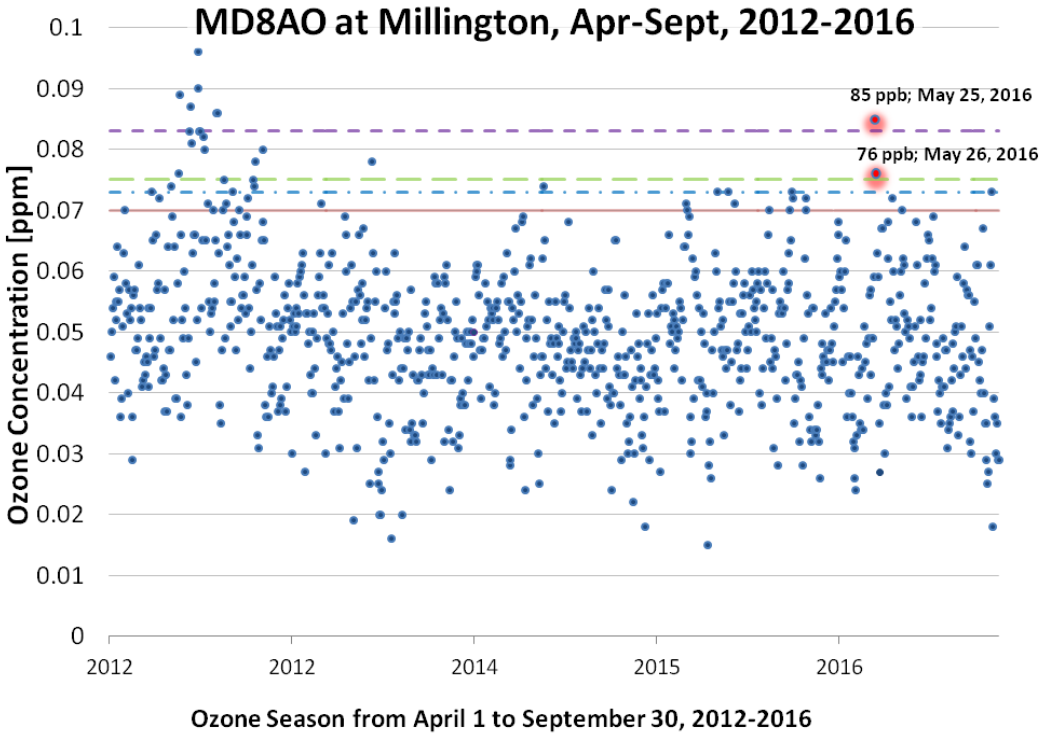


Figure 28. As in Figure 19 except for Millington.

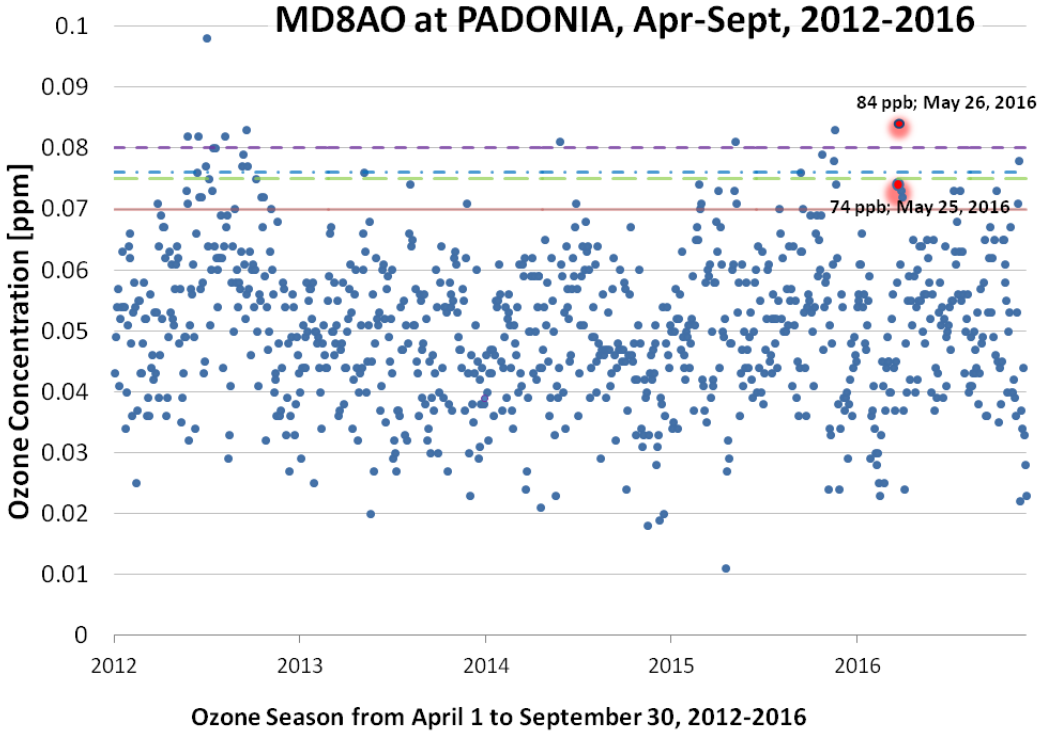


Figure 29. As in Figure 19 except for Padonia.

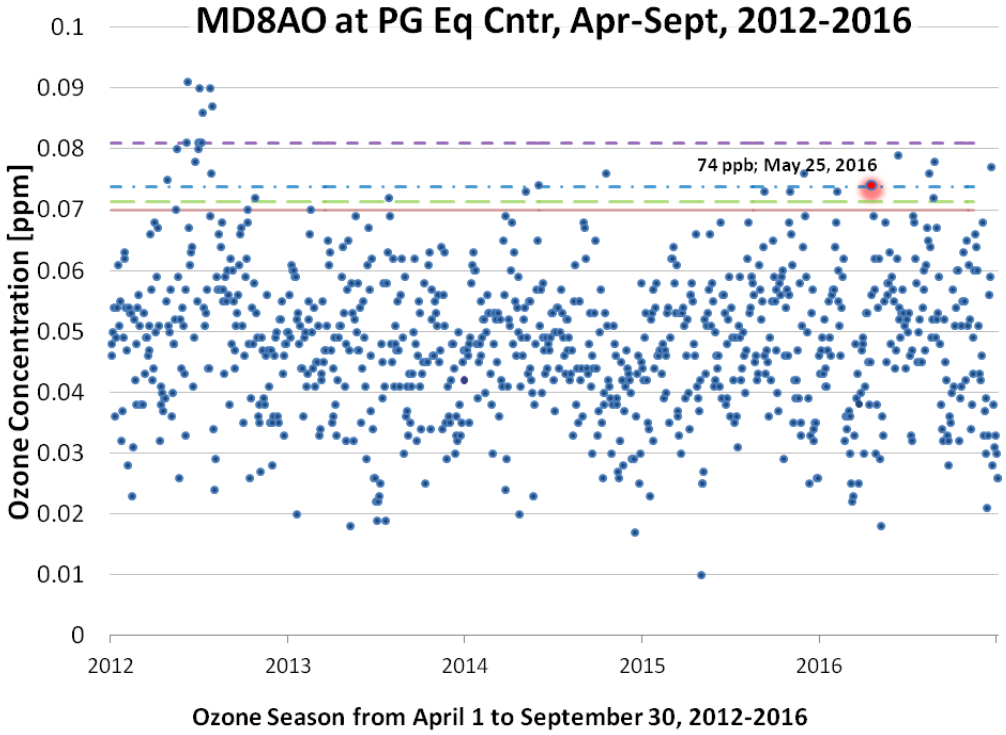


Figure 30. As in Figure 19 except for PG Eq Cntr. MDE is seeking exclusion of only May 25, 2016.

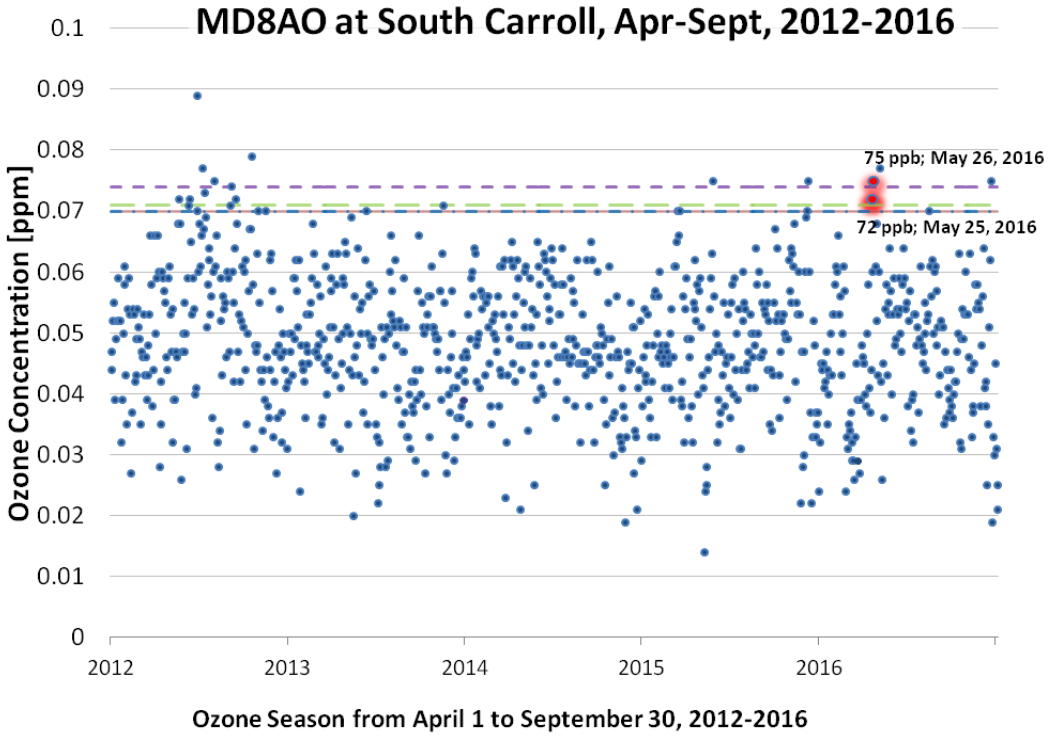


Figure 31. As in Figure 19 except for South Carroll.

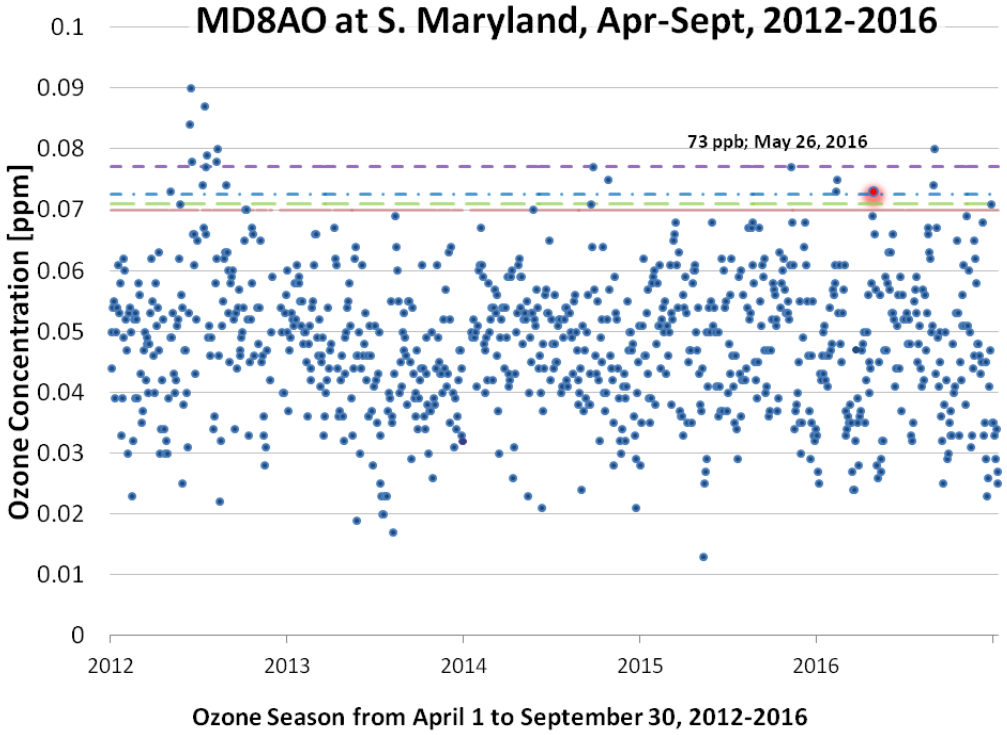


Figure 32. As in Figure 19 except for S. Maryland. MDE is seeking exclusion of only May 26, 2016.

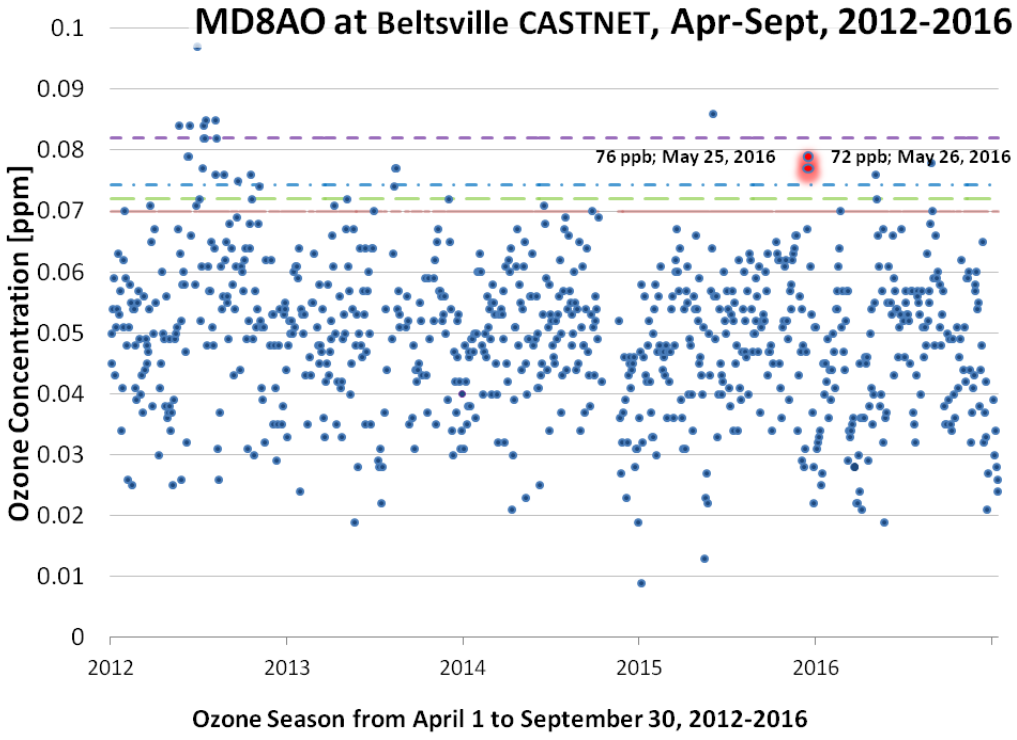


Figure 33. As in Figure 19 except for the Beltsville CASTNET monitor.

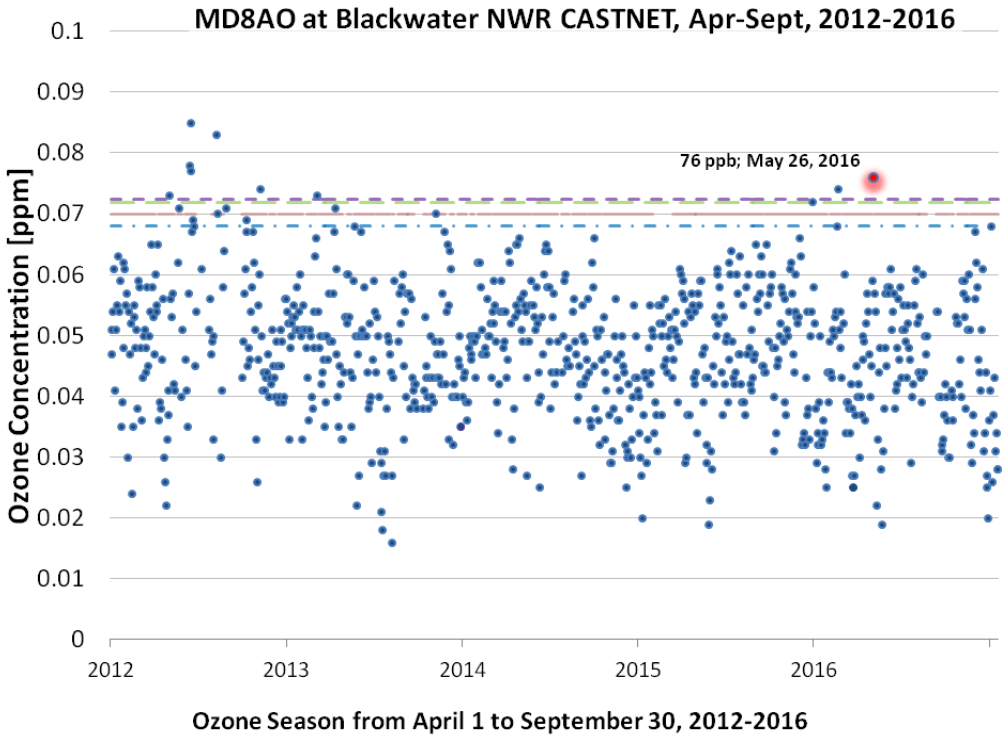


Figure 34. As in Figure 19 except for the Blackwater, NWR, CASTNET monitor. MDE is seeking exclusion of only May 26, 2016.

The preponderance of the monitors for which MDE is seeking as being influenced by an exceptional event show a "distinctive level" of monitored ozone concentration which were also within the top four highest MD8AO concentration of the 2016 season. Concentrations during the smoke influenced event exceeded the 99th percentile of not just May but also the entire mulit-seasonal dataset. Therefore, the May event is exceptional in nature. MDE has observed concentrations as those seen in May 2016 previously, such as during mid-summer of the 2012 ozone season, but with greater anthropogenic NOx emissions. The uncharacteristically high ozone concentrations early (May) in the 2016 ozone season, particularly in light of the huge precursor reductions over the past five years, and the large spatial coverage of the exceedances as compared to previous exceedances (see Figure 5), all suggest the monitors were influenced by wildfire smoke. MDE believes the evidence presented thus far indicates a clear causal relationship. Additional supportive analysis is presented below.

3.2. Evidence that Fire Emissions were Transported to Maryland

To further demonstrate that the Fort McMurray wildfire emissions were transported to Maryland, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT; Rolph, 2015; Stein et al., 2015) model was used to approximate the movement of air parcels both forward from the fire and smoke region and backwards from Maryland. According to the conceptual model, an intense burn period from May 17-19 created a prodigious smoke plume which was transported eastward, then moved southward over the Great Lakes and Midwest around May 21, 2016. Starting from May 20, which was after the intense burn period

and when the plume of smoke was already lofted in the atmosphere, a matrix of forward trajectories centered on the area which the HMS analyzed smoke across south central Canada were run (Figure 35a). Meteorological data driving these trajectories was the 12km North American Model (NAM). Running a matrix of trajectories (several trajectories which start from a gridded pattern over the source area) instead of a single trajectory allows the trajectories to show a spread of possible dispersion of the smoke plume while increasing the confidence in the general transport pattern of it. Due to increasing model error with time (an intrinsic occurrence when modeling the atmosphere) no single trajectory should be considered representative of the exact path of the smoke plume, and the longer the trajectory is run, the greater the error of the modeled path is likely to be. Therefore, clusters of trajectories increase confidence of the path of the smoke.

Two trajectory clusters are apparent in Figure 35a. The first is from the northern portion of the matrix, which stays north of the CONUS across Canada. The second is a cluster of trajectory members originating on the southern side of the matrix which work their way southeastward across the upper Midwest and Great Lakes. This corresponds to the forward transport of the plume observed from satellite and via ground measurements into and through the Great Lakes/Midwest and then in to the Mid-Atlantic. Three trajectories in aggregate, one red (A), one blue (B), and on Green (C), together (shaded area) represent transport to Maryland from the source region. All three trajectories take a full 4-5 days to transverse the distance to the east coast, which is consistent with heightened ozone taking until May 23/24 to develop across the Midwest/Great Lakes which led to exceedances on May 25 in Maryland. General subsidence (sinking motion) was also noted for nearly all members in the matrix (see vertical profile at bottom Figure 35a) with a majority of members at or below the original starting height of 1,500 m, supporting the assertion smoke aloft subsided to the surface under the ridge and/or behind the weak cold front on May 19.

Backward trajectories had a similar path to the southeast quadrant of forward trajectories (Figure 35b). As discussed in the conceptual model, the smoke plume was transported across the Great Lakes southward over the course of a few days while under high pressure. According to the back trajectory starting over Maryland at 1,500m on May 25 (green, Figure 35b), lofted smoke originally over 3,000m above ground level subsided to around 1,500m where it could be mixed into the boundary layer as early as May 23 over the Great Lakes area. Cross reference the path of this back-trajectory with Figure 18c to see that HMS analyzed smoke over the area of southern Canada on May 20 (where the backwards trajectory ends in Figure35b). Eventually, the smoke plume was transported east and far enough south such that Maryland was on the southern fringe of the plume. The time of transport (4-5 days) is in relatively good agreement with bringing the smoke plume analyzed on May 20 across the Northern Plains and Southern Canada southeastward to over the Great Lakes and into New England as previously discussed. Morphology in the upper levels turned transport from the north across the Midwest and Maryland to the west on May 24 and is reflected as the turn of the backwards trajectories across the Midwest to deliver the smoky and now ozone-laden airmass to Maryland.

The vertical displacement of the backwards trajectories is consistent with the increase in temperatures of the upstream airmass across the Midwest and indicates that additional smoke mixed down from a

substantial altitude. Trajectories around 500m ending over Maryland on May 25 (Figure 35b) dropped over 2,000m during transit to Maryland. Compressional heating of ~10°C/km (adiabatic rate) over 2,000m results in an increase of 20°C. Morning analysis (12z [8am LDT]) across central Canada on May 20 showed aloft temperatures of -3°C to -4°C. This corresponds to temperatures of around 15°C after dropping 2,000m to lower heights. The subsidence creating the temperature increase also brought down ozone precursors within the smoke across the central Midwest, particularly by May 23, as identified on the vertical cross section of the backwards trajectories (Figure 35b). The subsidence explains the above normal temperatures across the duration of the event and provides evidence that the boundary layer was well mixed thermodynamically, and thus, was also mixed with smoke and ozone precursors.

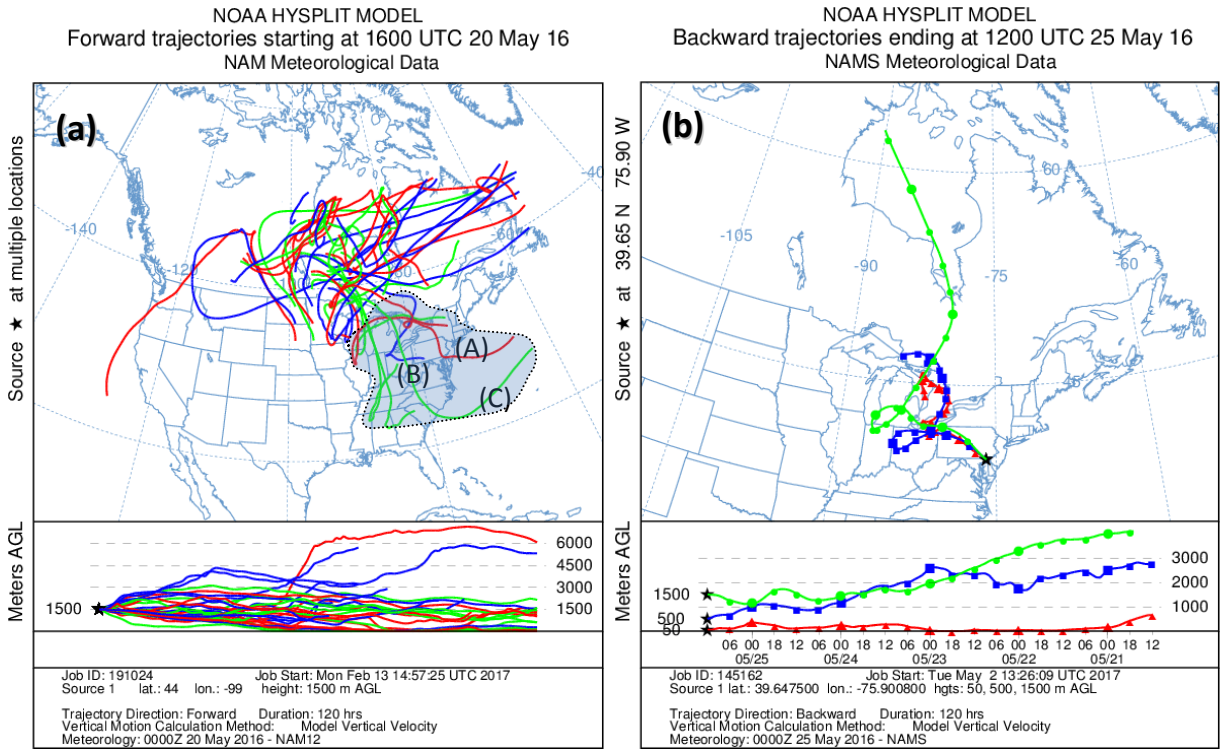


Figure 35. Forward and Backward Transport Trajectories
(a) A Matrix of 120-hour (5 day) North American Model (NAM) forward trajectories with starting points centered around the location of the smoke plume on May 20, 2016 across the upper Midwest and southern Canada. The trajectories show general clockwise transport fanning outward from the trajectory start locations. The southeastern quadrant of the trajectories (blue shading) held the relevant transport of smoke in to the upper Midwest, Northeast and Mid-Atlantic, including Maryland. (b) 120-hour back trajectories from northeast Maryland beginning on May 25 showing transport from the area of the smoke and Fort McMurray in to Maryland over the course of 4-5 days. Trajectories at 50-500m dropped over 2000m during transport to Maryland. Annotations (A), (B) and (C) mark trajectories mentioned in the text.

3.2.1. Evidence of Ozone Transport via Ozonesondes

MDE contends the ozone formation from the Fort McMurray fires occurred upstream of Maryland and the ozone was transported to Maryland as the cause of the ozone exceedances above the 99th percentile of recent historical data. With a modifying, aging and degrading airmass evident across the Midwest and Great Lakes as of May 23 and 24, MDE requested ozonesondes on be launched May 25, 26, and 27 from the Howard University (HU-)Beltsville site (see Figure 2). These ozonesondes recorded substantial ozone

concentrations within the nocturnal residual layer (i.e., pre-dawn, ozone above the surface). At night ozone is removed from the layer of air a few tens of meters from the surface as it interacts with other molecules or objects. However, the layer of air immediately above the surface at night "preserves" ozone overnight making it the "transport relevant" layer or simply known as "the residual layer." The residual layer is usually found from around 500m to 1,500-2,000m above ground level at night. Therefore, surface ozone may be at or near zero ppb at night while just a few hundred meters above the ground ozone may still be 50-80 ppb. During the pre-dawn hours of May 25 ozone concentrations within the residual layer (0.5 – 2 km) were 70-75 ppb (Figure 36). Wind direction at the time showed transport in this layer was from approximately 300 to 345°, or northwesterly.

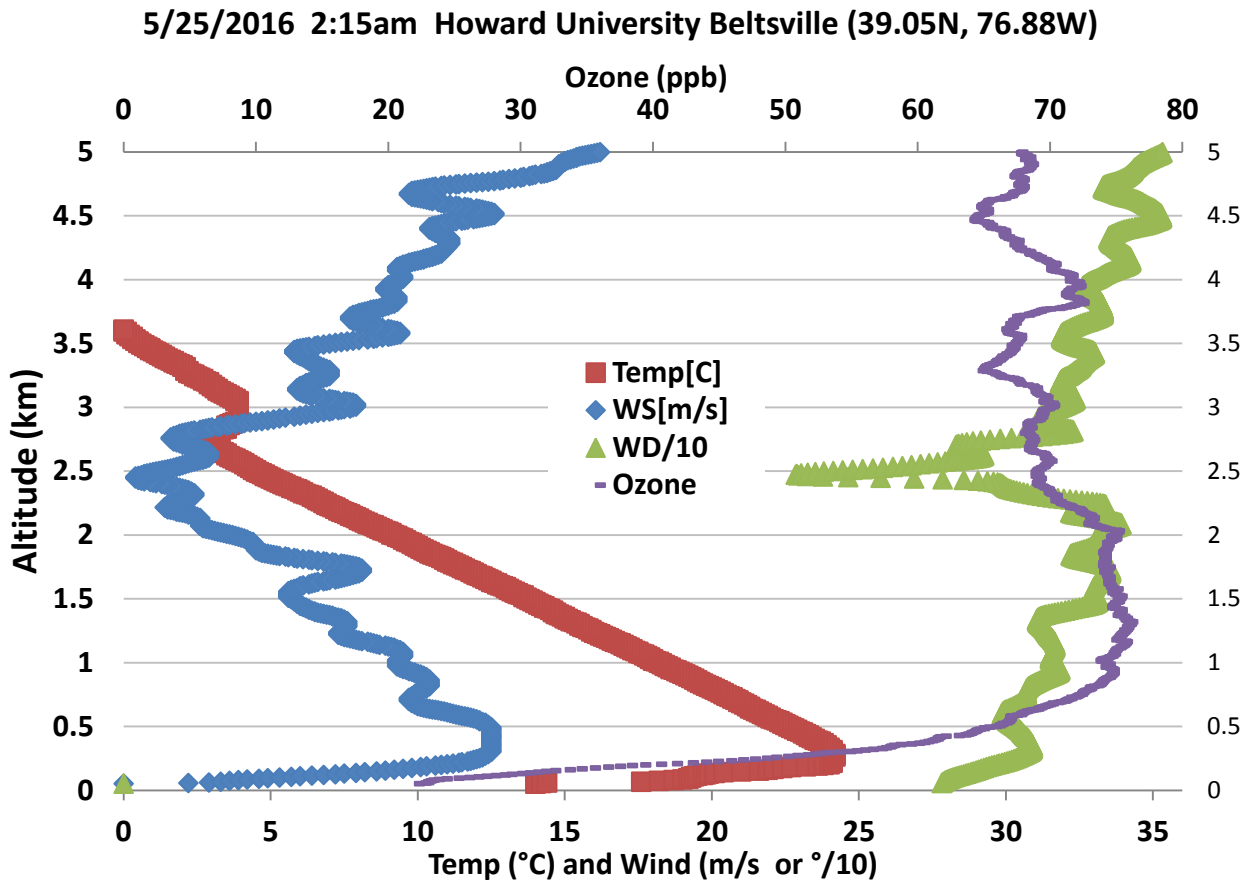


Figure 36. Ozonesonde launched from Howard University Beltsville on the morning of May 25, 2016. Temperature (red, squares), wind direction (green, triangles), wind speed (blue, diamonds), and ozone (purple, dashes) are shown from the surface through 5km AGL. Ozone concentration is given on the top horizontal axis. Temperature and winds are given by the bottom horizontal axis.

Further analysis of the origin of the air parcels transporting enhanced ozone within the residual layer showed transport from eastern OH and western PA. HYSPLIT trajectories on the morning of May 25 showed westerly transport from Ohio from May 24 and 25 to the HU-Beltsville site (Figure 37). The meteorological data driving the comparison trajectories was from the 12km resolution North American Model (NAM) and 32km resolution North American Regional Reanalysis (NARR) datasets. The trajectory levels chosen were

based on ozonesonde features (Figure 36) which were the low-level wind maximum (jet) at approximately 400m (Figure 37: red lines, triangles), and the residual layer, which had a layer of well mixed ozone beginning at about 1,000m (Figure 37: blue, squares) and middle around 1,500m (Figure 37: green, circles). The backwards trajectories combined with the ozone concentrations measured in the residual layer by the ozonesonde (Figure 36) showed transport of modified air containing ozone greater than 70ppb from the eastern Midwest (Figure 37). Said differently, the same air containing heavy ozone concentrations over the eastern Midwest on May 24 was sampled by the ozonesonde in Maryland on the morning of May 25.

Compare the origin of the trajectories from central Ohio (Figure 37) to ozone concentrations across the same area (Figures 18f and 18g). Central and southern Ohio into Appalachia (West Virginia, eastern Tennessee) generally did not have surface ozone concentrations that exceeded the 70ppb 8-hour standard on May 23 and were on the southern fringe of the highest ozone over the Great Lakes. That same southern extent of ozone pushed east and southeastward into Maryland on May 25 and created a sharp gradient in surface ozone concentrations south of DC. Said another way, Maryland was on the southern fringe of the ozone-laden airmass on May 25 and 26, consistent with surface ozone concentrations decreasing quickly southwest of DC. Surface analysis the previous day supports the conclusion that the smoke was likely transported around southern Ohio and West Virginia but then pushed southeastward in to Maryland. The winds across Ohio were circulating around the periphery of the surface high pressure system (Figure 38). The clockwise flow may have been enough to keep smoke concentrations in Ohio slightly lower than locations just a bit farther north. Trajectories across Ohio show a slight rising (vertical) motion along their path (right side of trajectory vertical cross sections in Figure 37). It was possible that because the high pressure was weakening it no longer had strong subsidence at the high center to support an ozone exceedance of 70ppb. Still, even if not at exceedance levels, ozone concentrations were enhanced across Ohio (southern edge of degraded airmass) which was instrumental in development of a residual layer which was transported into Maryland on May 25. The ozonesonde observed ozone within the residual layer transported from areas upstream which were impacted by smoke on May 24.

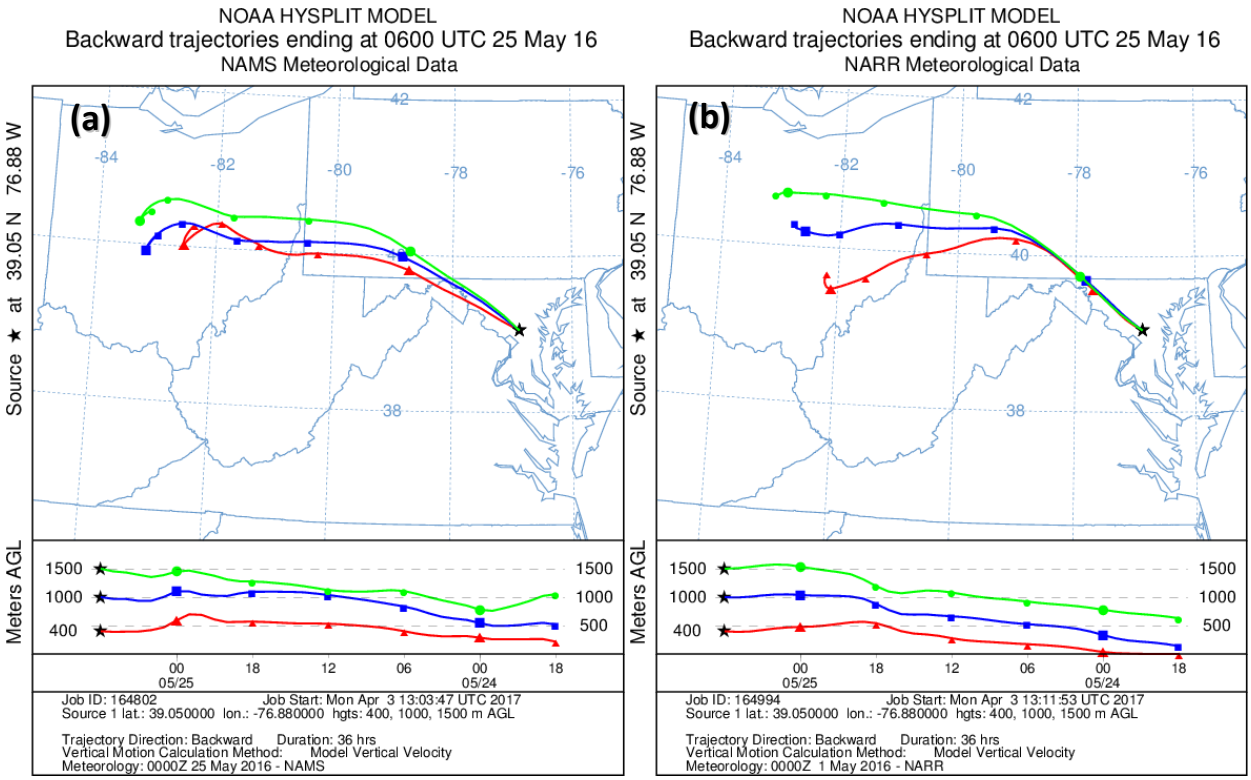


Figure 37. HYSPLIT trajectories for the ozonesondes on May 25, 2016.
The trajectories shown are 36 hour backwards trajectories beginning at the time of the ozonesondes launched at the HU-Beltsvillle site in Maryland at 2:15am (0600 UTC) on May 25 for the NAM (a) and NARR (b) meteorological datasets. The height chosen (1500m, green; 1000m, blue; 400m red) are based on features within the ozonesonde, namely the low level wind speed maximum (red), the bottom of the residual layer (blue) and the middle of the residual layer (green). The NAM and NARR datasets are shown for comparison.

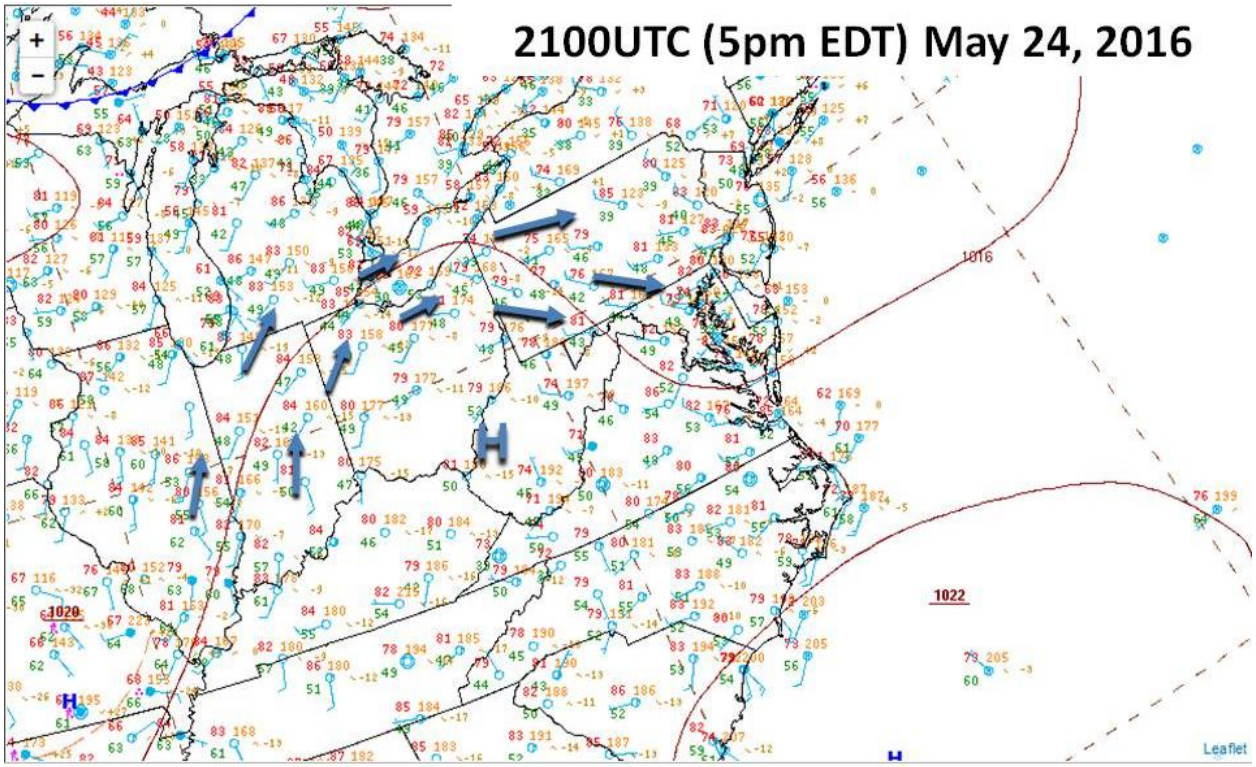


Figure 38. Surface analysis on May 24, 2016 at 5pm local time.
The blue arrows show that based on surface flow much of the smoke laden airmass was likely transported around southern Ohio and West Virginia. This is consistent with Maryland being placed on the southern fringe of the high ozone on May 25 as transport came from the northwest.

A similar magnitude of ozone concentrations aloft was observed on the morning of May 26 as on May 25, though the ozone was not distributed as uniformly. The May 26 pre-dawn ozonesondes recorded maximum ozone above 75ppb within the residual layer between 2.5 and 3 km in height (Figure 39). Based on the inversion in the temperature profile around 2km (an inversion is where temperature no longer decreases with increasing height), this may be another layer of air with slightly different characteristics than the layer between 0.5km and 2km where ozone ranged from 60 to 70ppb. Regardless, high ozone persisted above the surface overnight from May 25 to May 26, 2016. The highest ozone concentrations between 2 and 3km were associated with winds from about 300°, slightly more westerly than May 25 but persisting from areas that on previous days recorded high ozone. Nearer the surface, particularly below 1.5km, winds were more west southwesterly (~250°). This was consistent with less smoke-influenced and ozone enhanced air being transported to the state since these regions (i.e., areas south of the Ohio River) were less impacted (though not "un-impacted") by high ozone than areas across the Great Lakes area (see Figure 18). Indeed, ozone concentrations generally decrease in the layer of transport below 1.5km to values below 70ppb as measured by the ozonesonde. The pattern of transport is similar above 3km as well where ozone decreases where winds turn towards the southwest.

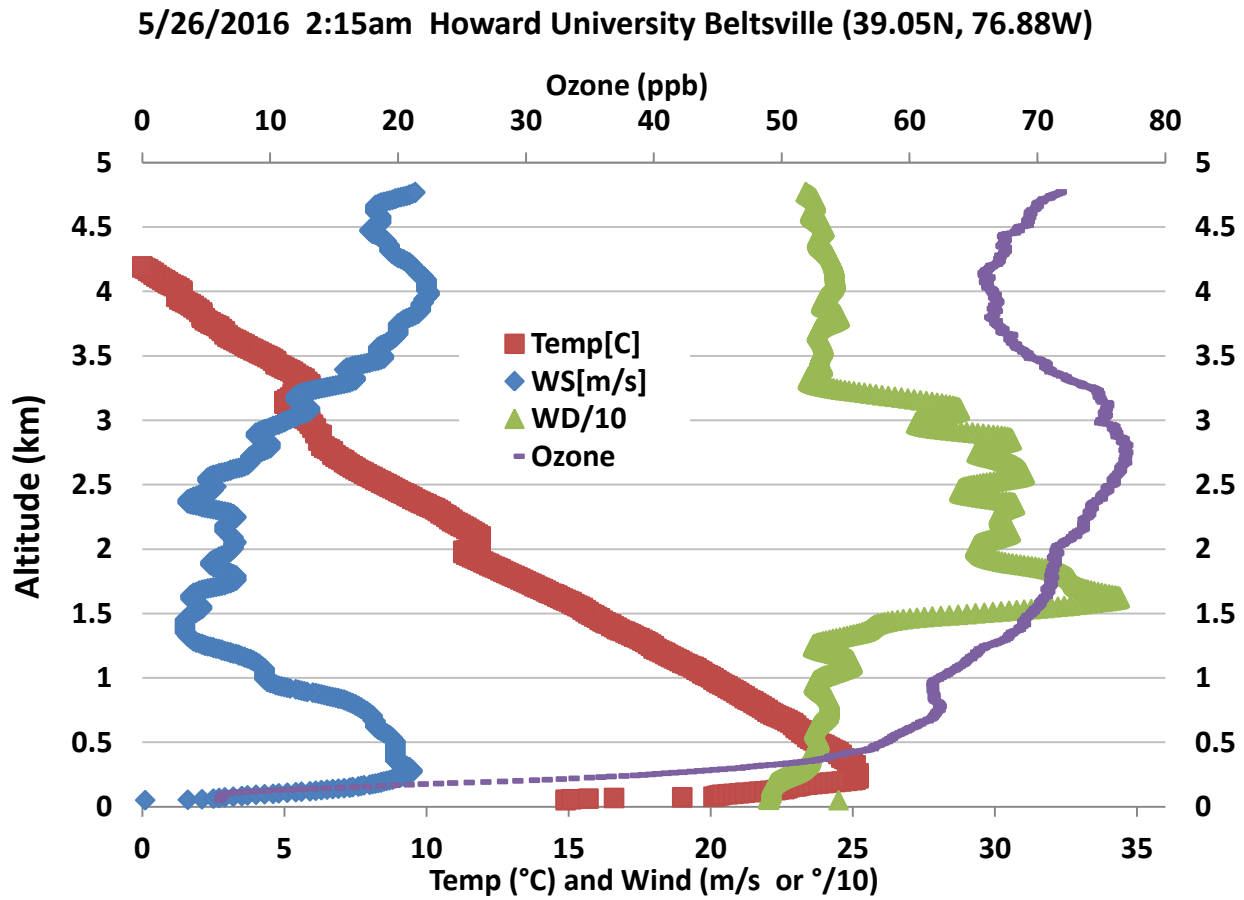


Figure 39. Ozonesonde for May 26, 2016.
Same as figure 37 but for May 26.

HYSPLIT trajectory analysis was repeated for the May 26 ozonesonde in similar fashion to the May 25 ozonesonde (Figure 40). For the May 26 ozonesonde, trajectory levels were picked at 500m, 1,500m and 2,700m to capture increased ozone concentrations within the low-level wind speed maximum, wind direction shift within the residual layer, and the peak ozone concentration within the lowest 5km, respectively. As on May 25, 36-hour back trajectories originating from HU-Beltsville were constructed for each of these heights using both the NAM (Figure 40a) and NARR (Figure 40b) meteorological datasets. Dissimilar to May 25, May 26 showed discrepancy in the trajectories between the two data sets. The discrepancy was believed to be due spatial resolution of the model attempting to capture the slowly evolving, weakly forced pattern between May 25 and 26, 2016. However, two features were consistent between the data sets. First, westerly transport was observed at 1,500m. Second, there was a trend towards southerly (cleaner) transport. The backing (counter-clockwise tendency) trend in the trajectories (as compared to May 25) was consistent with eventual southerly clean-out by May 27 (Figure 41), which resulted in the dispersal of the smoke from the region.

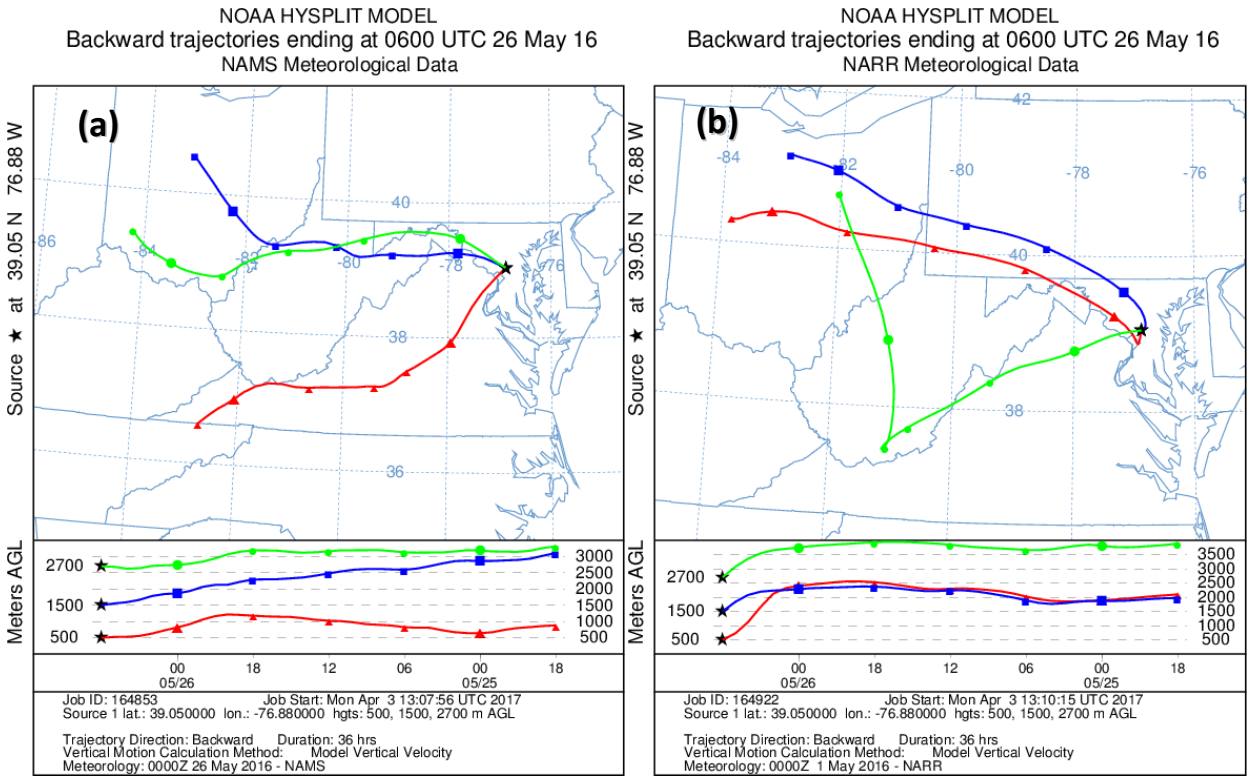


Figure 40. HYSPLIT trajectories for the ozonesondes on May 26, 2016.
The trajectories shown are 36 hour backwards trajectories beginning at the time of the ozonesondes launched at the HU-Beltsville site in Maryland at 2:15am (0600 UTC) on May 26 for the NAM (a) and NARR (b) meteorological datasets. The height chosen (2700m, green; 1500m, blue; 500m red) are based on features within the ozonesonde. Namely the low level wind speed maximum (red), the bottom of the residual layer (blue) and the peak in ozone concentrations seen the May 26, 2016 ozonesonde (green). Two meteorological datasets are shown for comparison.

Both ozonesondes and accompanying backwards trajectories verify that an airmass characterized by substantial ozone within the residual layer was transported into Maryland from areas (i.e., Ohio) which on previous days were on the southern periphery of the highest ozone concentrations augmented by smoke from Canada. While some ozone persisted in the residual layer on May 27, the concentration decreased in comparison to May 25 and 26, and was associated with cleaner transport from areas that had lower ozone on previous days. Winds from the southwest were apparent through a larger depth of the lower atmosphere on May 27 (Figure 41) which caused MD8AO to decrease in Maryland as compared with May 25 and 26 as ozone within the residual layer decreased (Recall that residual layer ozone will mix downwards and mix with local emissions the next day. Thus, lower concentrations in the residual layer mean less ozone is added to local ozone during the day). Ozone values were not greater than 65ppb through the depth of the atmosphere, with winds from approximately 240° (southwesterly) through that same depth. In summary, west and northwest winds were associated with enhanced ozone concentrations as measured by the ozonesonde at the onset of the smoke event in Maryland, which came from areas already influenced by the smoke plume. Once winds turned to the southwest, the smoky air cleared the area, decreasing the ozone concentrations observed in the residual layer and thereby substantially decreasing the impact on surface ozone concentrations by May 27.

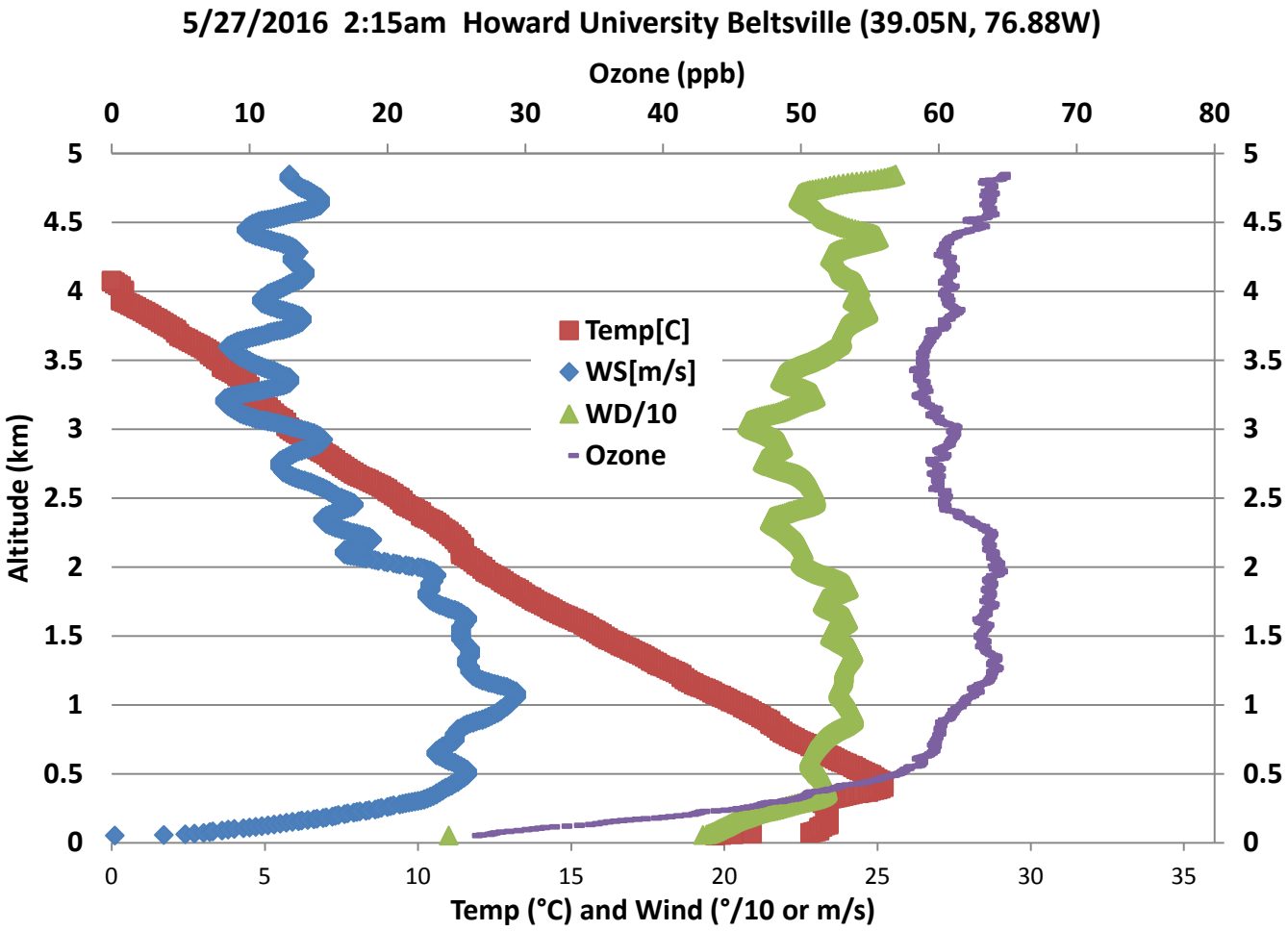


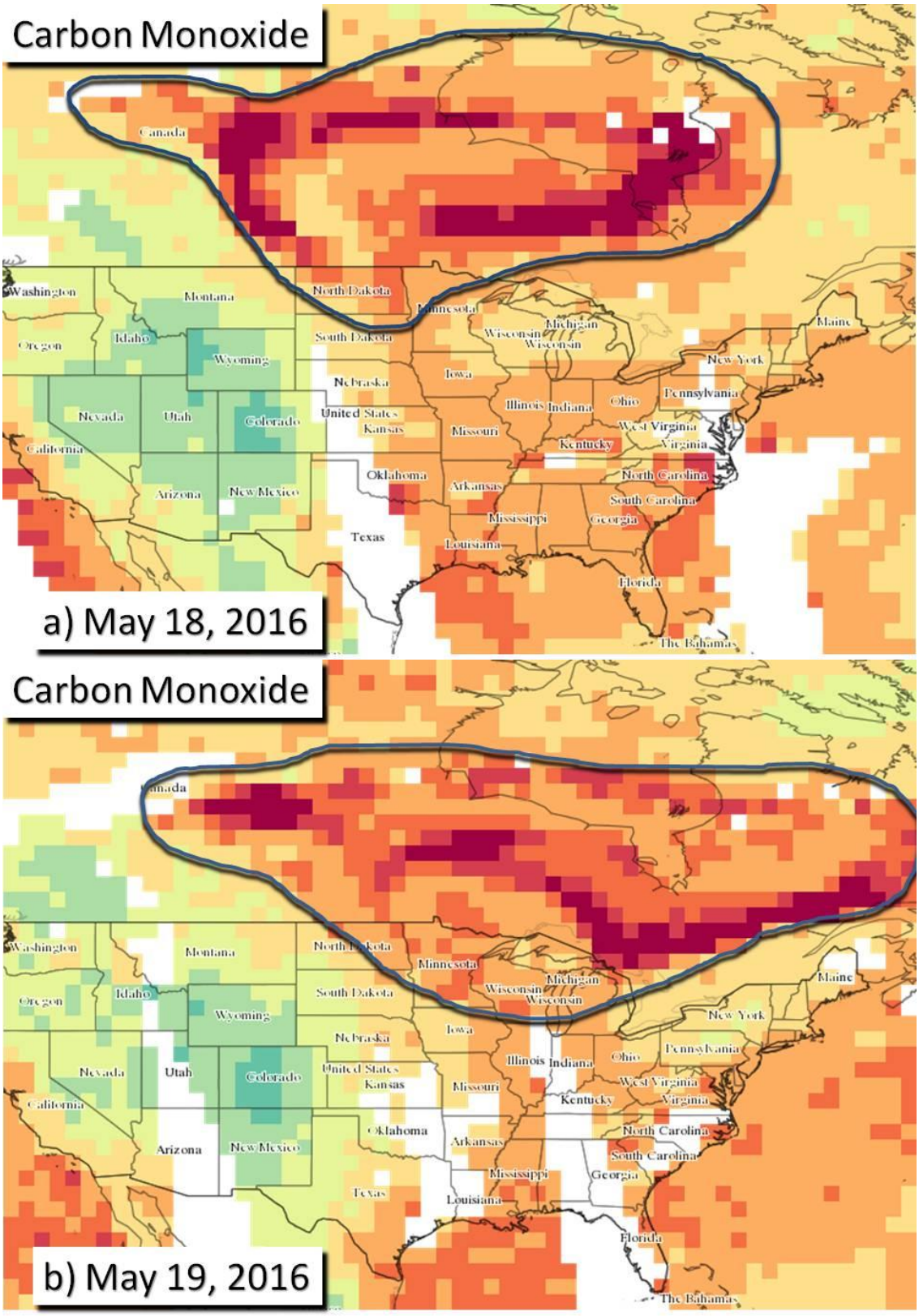
Figure 41. As in Figure 10 but for May 27, 2016.

Spatial and temporal analysis of ozone and smoke analyzed by HMS were presented in Figure 18. There MDE showed that the track and evolution of ozone which came from the northern Midwest of the CONUS was spatially correlated with analyzed smoke from May 18 through May 26. This was consistent with aloft winds observed by ozonesondes (Figures 36 and 39). In Maryland specifically, MD8AO was also greatest at the monitors directly under HMS analyzed smoke. For example, on May 25, the highest ozone concentrations were located at Fair Hill near the Pennsylvania line and at Millington on the northern eastern shore; smoke was specifically analyzed over both locations. Smoke was analyzed over the northeast portion of the state on May 26 as well where concentrations were again the highest (e.g., Padonia, Furley, Edgewood, Essex). The pattern of highest ozone under analyzed smoke was also true prior to the exceedances on May 24 in Maryland. The Piney Run, Hagerstown, and Frederick ozone monitors all had the highest MD8AO concentrations at 63, 62 and 62ppb, respectfully, on May 24, when smoke was analyzed above these western Maryland sites, which received transport of the ozone rich airmass first among Maryland monitors and therefore had the greatest time on May 24 to produce ozone before the main portion of the degraded airmass arrived in the state. Note that the Piney Run site recorded an MD8AO

concentration of 63ppb and 64ppb on May 24 and 25, respectfully. At an elevation of 766m (2,513ft), the location measures the lower portion of the residual layer. The Piney Run concentrations closely match the observed ozone concentrations on the morning of May 25 at the same altitude on the ozonesonde. Hourly observations at Piney Run at the same time as the ozonesonde on May 25 were 55 and 56ppb at 1 and 2 am EDT (not shown). Thus even the hourly concentrations observed at Piney Run were consistent with elevated ozone observed by the ozonesonde (72ppb) as shown in Figure 36. The difference in both the MD8AO and hourly observations was due to nocturnal titration (in the hourly observations) at the surface site, dry deposition during both day and night (ozone hitting nearby trees, etc.) and due to Piney Run remaining on the southwestern fringe of the highest concentrations transported in to Maryland.

3.2.2. Evidence of Wildfire Emissions via Satellite

Smoke analyses from the HMS already showed a plume of smoke being transported across the Great Lakes and Midwest towards Maryland and the northeastern CONUS. Satellites retrievals are capable of tracking wildfire species as well. When in combination with the expertly analyzed HMS smoke plume, they can together provide irrefutable evidence of the transport of wildfire ozone precursors. CO has been previously identified as a wildfire smoke indicator (Andreae and Merlet, 2001; McKeen et al., 2002, DeBell et al., 2004, Dreessen et al., 2016) and can play a role in ozone production. Total column CO (that is the sum of the CO between the ground and the satellite, most of which is near the ground unless lofted as a consequence of a large combustion source) was observed to follow a pattern of transport similar to that of the ozone exceedance conceptual model (Figure 10). Initially on May 18 (Figure 42a) a large plume emanating from the Fort McMurray area was observed across southern Canada. The plume continued eastward on May 19 (Figure 42b) though began to move southward into the CONUS. This trend continued on May 20 (Figure 42c) as additional CO was analyzed again coming from the Fort McMurray area. By May 21 (Figure 42d) the CO plume moved southward down the Mississippi River Valley area of the CONUS but otherwise consolidated over a large area from Tennessee to the Hudson Bay and over the Great Lakes area. There the plume lingered on May 22 (Figure 42e) and May 23 (Figure 42f) while slowly dissipating in intensity as CO in the plume reacted with other species in the atmosphere. By May 24 the plume had begun to slide eastward and was analyzed over Maryland (Figure 42g). Evidence of the plume persisting across the northeast CONUS is present on May 25 as well (Figure 42h), however a missing satellite overpass prevents additional conclusions for May 25. However, interpolating between May 24, 25 and where the plume was observed on May 26 (Figure 42i) strongly suggests its presence over Maryland on May 25 as well, considering the plume still was over Maryland on May 26. Note that the observation of the plume over the eastern half of the state on May 26 was consistent with the analyzed smoke by HMS on the same date. This provides further evidence that wildfire emissions were indeed transported to Maryland on the two days in question: May 25 and 26, 2016.


Carbon Monoxide
Canada
Washington
Montana
North Dakota
Minnesota
Michigan
Wisconsin
Maine
Oregon
Idaho
South Dakota
Wyoming
New York
Iowa
Nebraska
Pennsylvania
Illinois
Indiana
Ohio
Nevada
Utah
Colorado
United States
Kansas
Missouri
West Virginia
Kentucky
Virginia
California
Oklahoma
Arkansas
North Carolina
Arizona
New Mexico
South Carolina
Mississippi
Georgia
Texas
Louisiana
Florida
The Bahamas
a) May 18, 2016
Carbon Monoxide
Washington
Montana
North Dakota
Minnesota
Michigan
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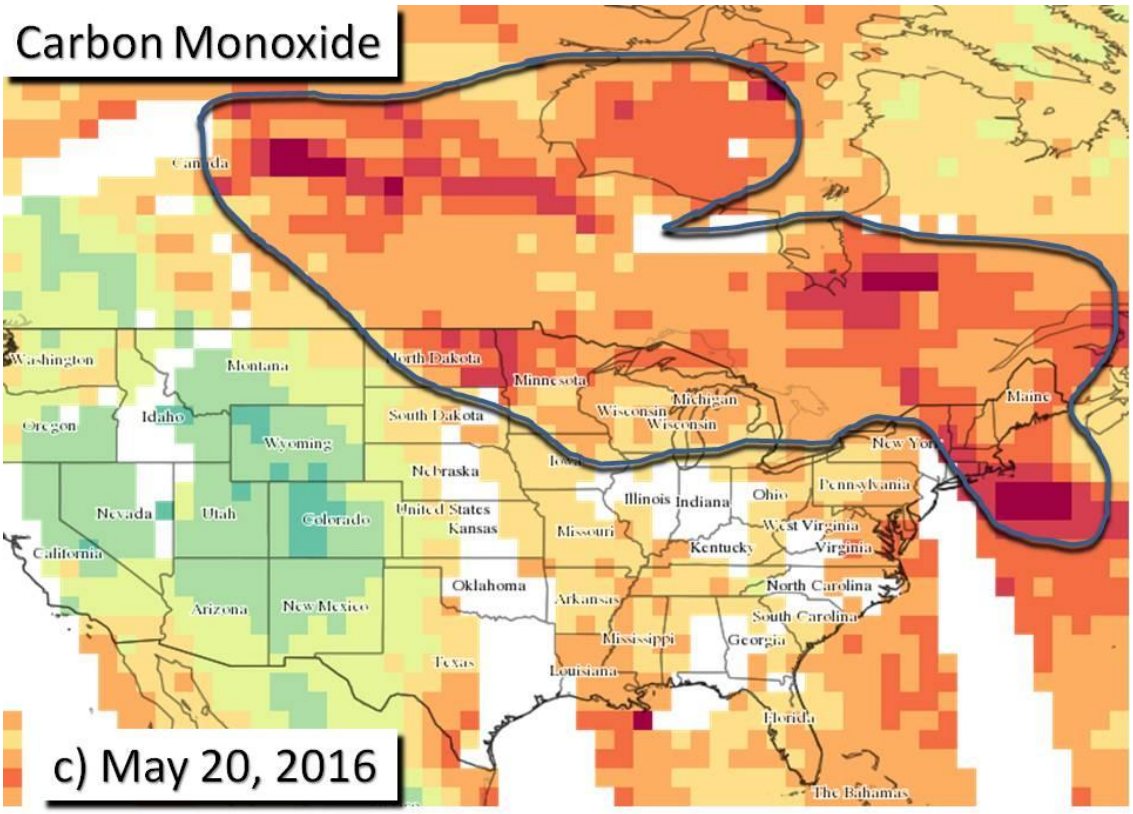
b) May 19, 2016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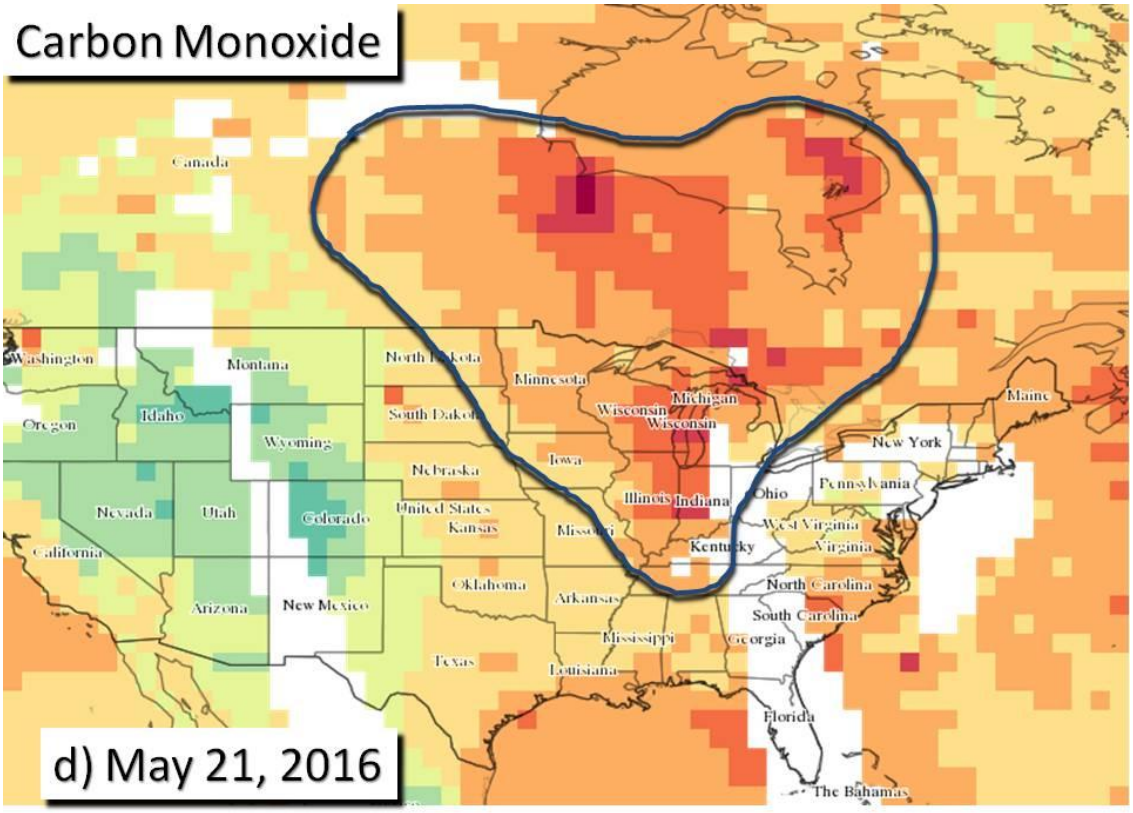
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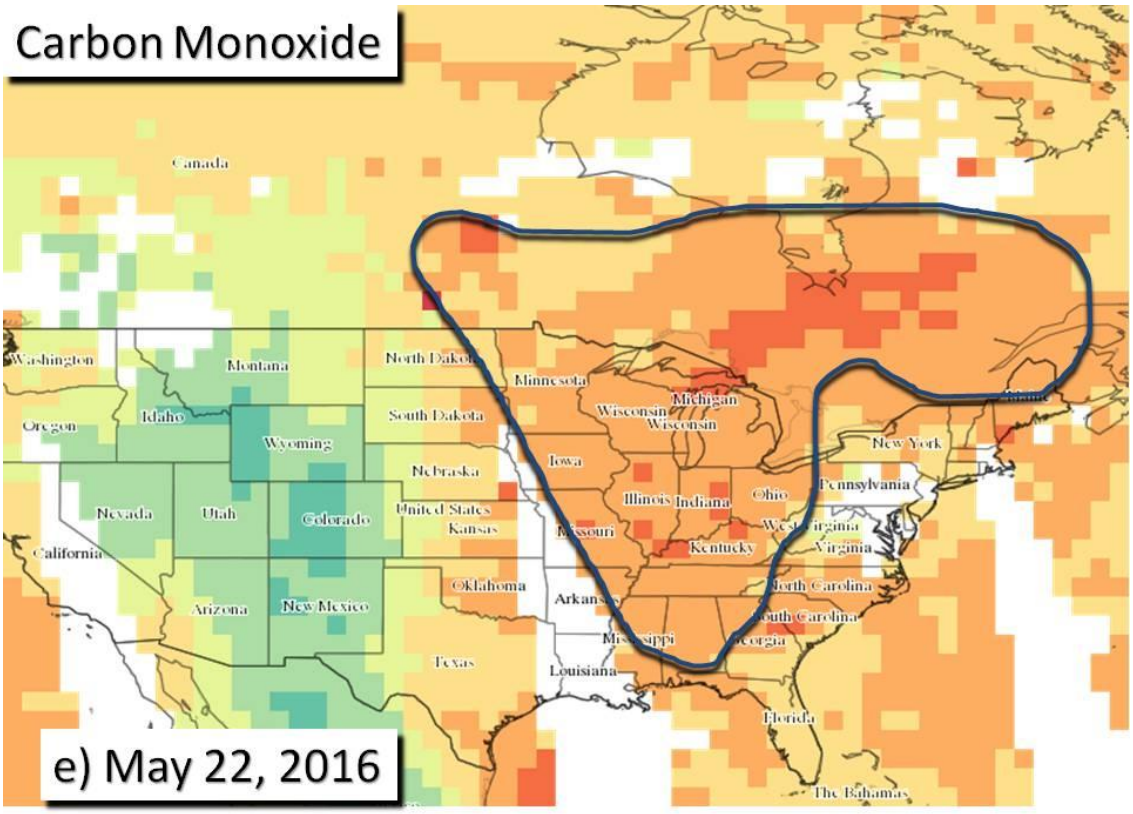
d) May 21, 2016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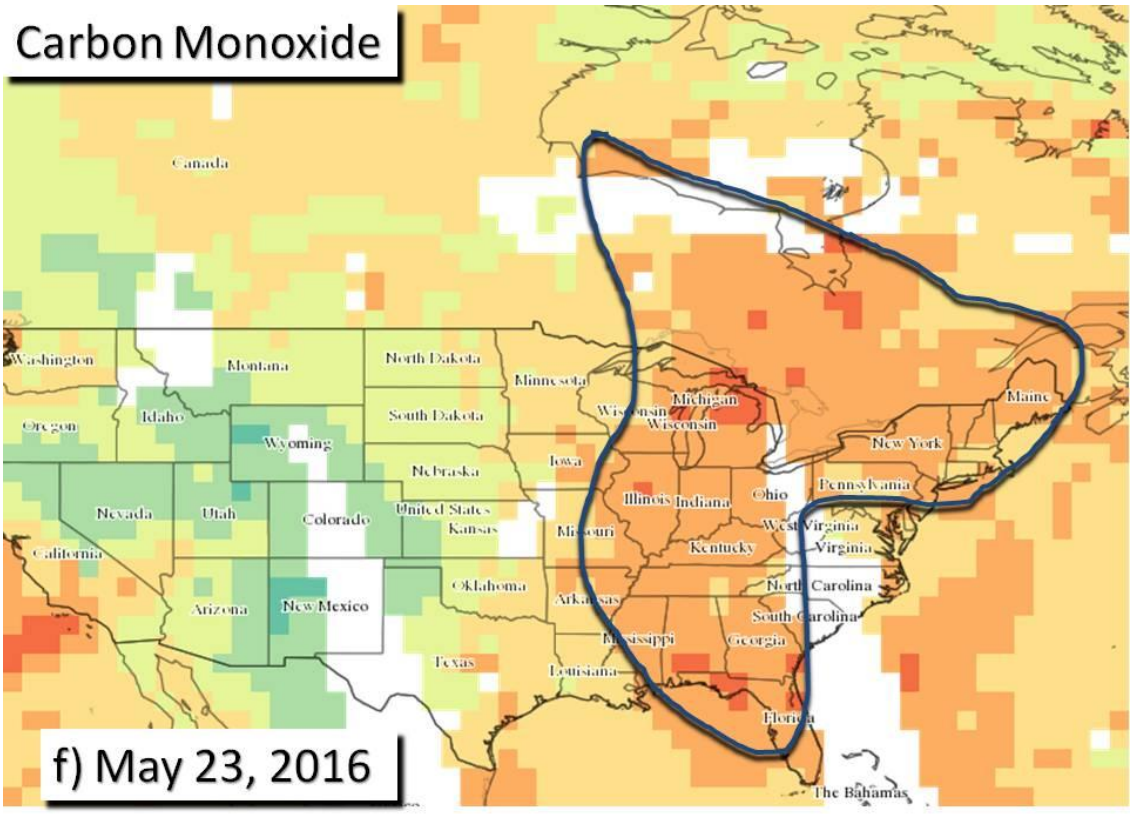
e) May 22, 2016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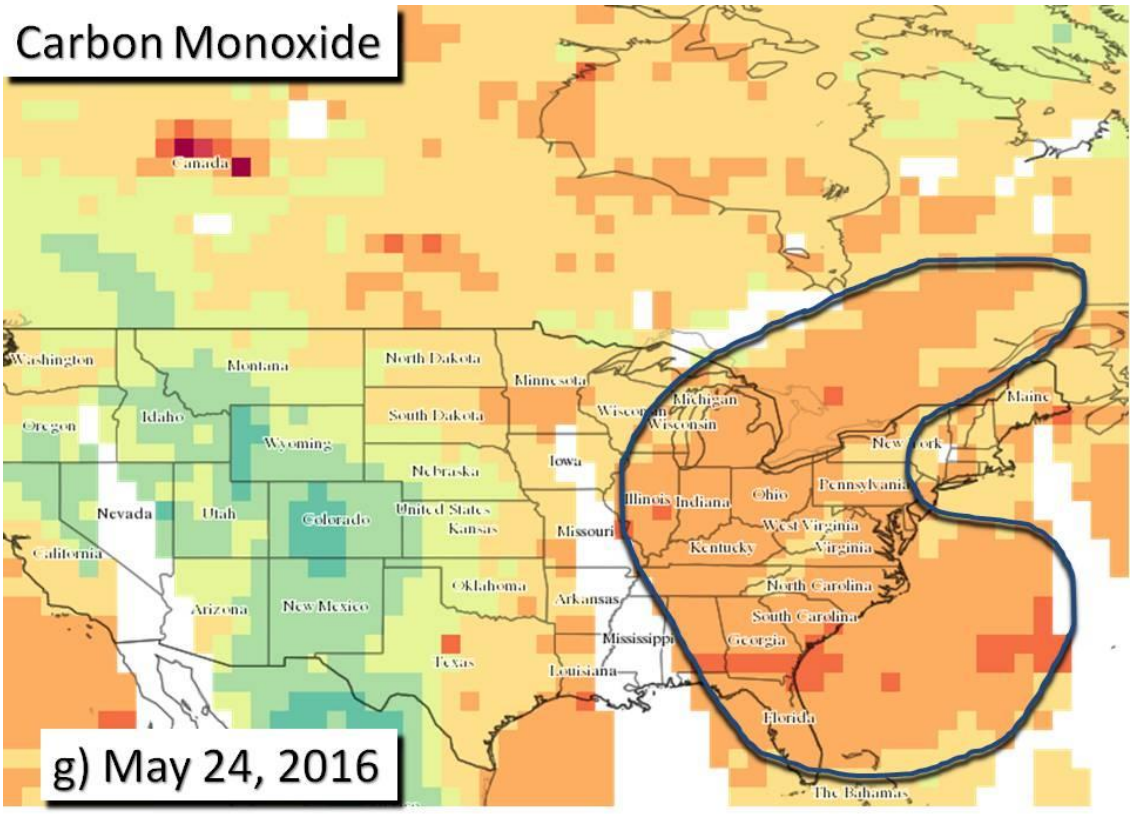
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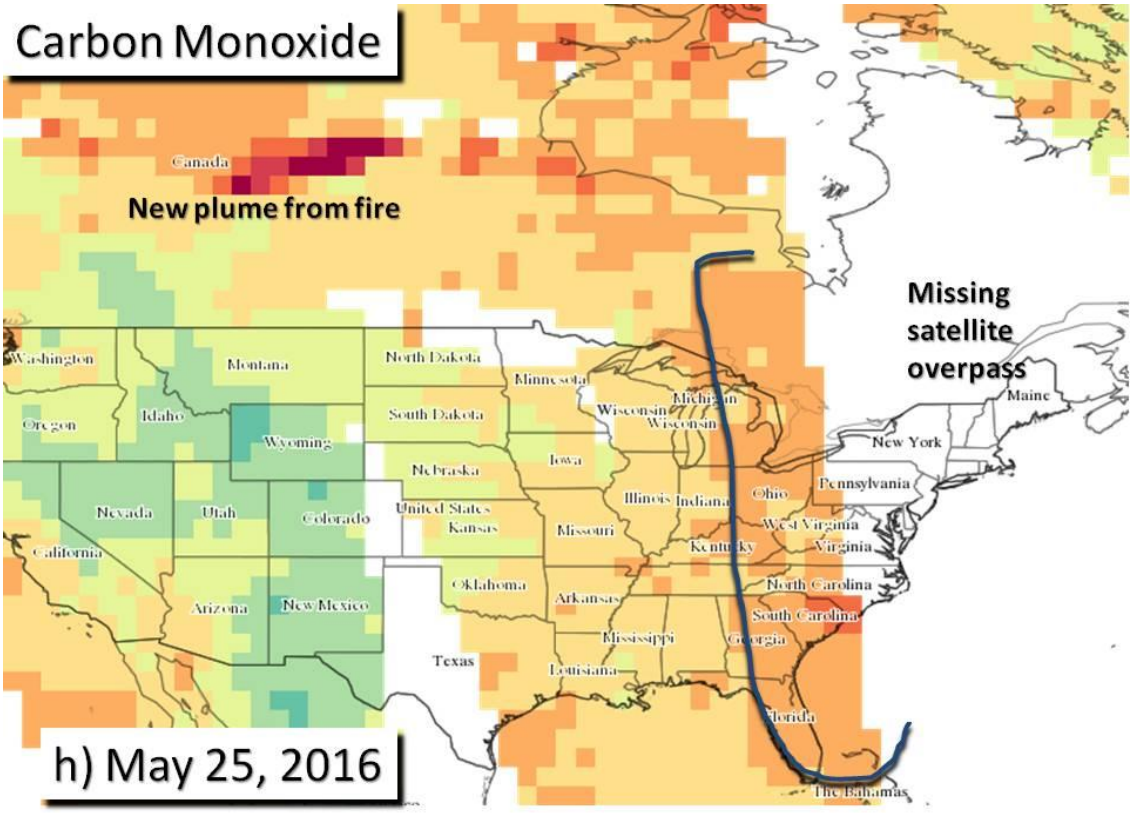
g) May 24, 2016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Missing satellite overpass
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h) May 25, 2016

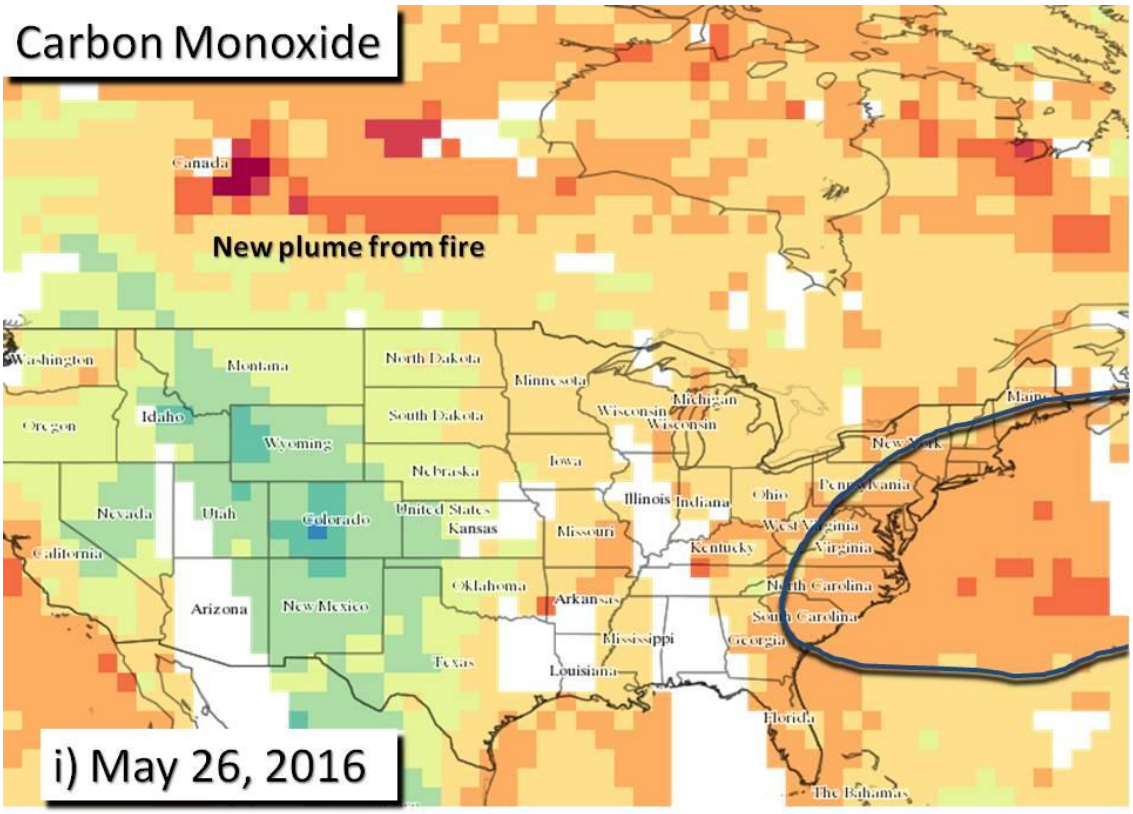


Figure 42. Carbon monoxide: total column for May 18-26, 2016.
A plume of carbon monoxide (CO) traveled from the Fort McMurray area. Darker reds indicate more CO in the atmospheric column. Greens and blues indicate low concentrations of CO in the column. The plume and its movement is identified by the bold line. NASA Giovanni data service provided access to the satellite retrievals https://giovanni.gsfc.nasa.gov/giovanni/.

3.3. Q/d Analysis

EPA guidance [Guidance on the Preparation of Exceptional Events Demonstrations for Wildfire Events that May Influence Ozone Concentrations, Final, EPA, September 2016] recommends conducting a Q/d analysis as a rough assessment of the ability of a wildfire to cause increased ozone concentrations. The Q/d analysis is simply a comparison of the ratio of Q, the daily tons of VOC and NOx emitted from the fire, to d, the distance in kilometers from the fire to the point of concern. If the Q/d value compares favorably to analytical data from other fires, then the fire can be presumed to have had a causal effect on ozone concentrations at the point of concern. The comparison to other fires is a key point that will be brought up again.

EPA guidance indicates that a fire should have a Q/d in excess of 100 tons per day per kilometer (tpd/km) in order to be considered to have a clear causal impact on ozone. EPA developed this value based on analyses of four fires which occurred in 2011. Due to the large distances which Canadian wildfire plumes must travel to Maryland, the Q/d analysis will regularly fail to achieve the 100 deemed acceptable by the EPA guidance.

Therefore, MDE feels the 100 value is not representative for long-range east-coast smoke events. MDE instead presents several alternatives based on this analysis.

3.3.1. Estimate of Q

The emissions from the fire can be estimated using information from EPA's AP-42 Compilation of Air Emission Factors Section 13.1 Wildfires and Prescribed Burning. The equations given are as follows:

Fi = Pi * L (Equation 1)
Ei = Fi * A (Equation 2)

Fi = emission factor (mass of pollutant/unit area of forest consumed)
Pi = yield for pollutant "i" (mass of pollutant/unit mass of forest fuel consumed)
= 12 kg/Mg (24 lb/ton) for total hydrocarbon (as CH4)
= 2 kg/Mg (4 lb/ton) for nitrogen oxides (NOx)

L = fuel loading consumed (mass of forest fuel/unit land area burned)
A = land area burned
Ei = total emissions of pollutant "i" (mass pollutant)

Combining equations 1 and 2, we have:

Ei = Pi * L * A

Pi is given above for total hydrocarbons and for nitrogen oxides. The fuel loading is given in AP-42 for different regions of the United States and ranges from 9 to 60 tons per acre. Conservatively, we will estimate a low end emission rate using 10 tons per acre which is associated with North Central US conifer forests. Note that our results could increase by a factor of 6 were the high end of emissions expected.

The Alberta government reported that by June 10, 2016 the fire ultimately covered 589,995 hectares (1,457,909 acres) with a perimeter of 996 kilometers (618 miles). For reference, the total land area of Rhode Island is approximately 270,000 hectares.[7] The chart below indicates the total area covered by the fire as reported by the Alberta government (Figure 43)[8]. During the days prior to the smoke plume entering US space (May 17- 21) the fire grew by approximately 149,000 hectares (368,187 acres).

Therefore, ignoring the smoldering of previously burned areas AND perhaps more significantly, any additional fuels burned within the Southern Canada fires (Figure 6) the total hydrocarbon emissions from the period can be estimated to be:
Ehc = 24 lbs of HC / ton of forest fuel consumed * 10 tons fuel / acre * 368,187 acres
Ehc =88,364,880 pounds of HC

[7] Any large area estimate is more comprehensible if compared to a familiar area such as the State of Rhode Island.
[8] https://www.alberta.ca/release.cfm?xID=41701E7ECBE35-AD48-5793-1642C499FF0DE4CF [Final Update 39: 2016 Wildfires (June 10 at 4:30 p.m.), Alberta Government]

Ehc = 44,182 tons of HC emitted during the period from May 17 to May 20

Similarly for NOx:
Enox = 4 lbs of NOx / ton of forest fuel consumed * 10 tons fuel / acre * 368,187 acres
Enox = 14,727,480 pounds of NOx
Enox = 7,364 tons of NOx emitted during the period from May 17 to May 20

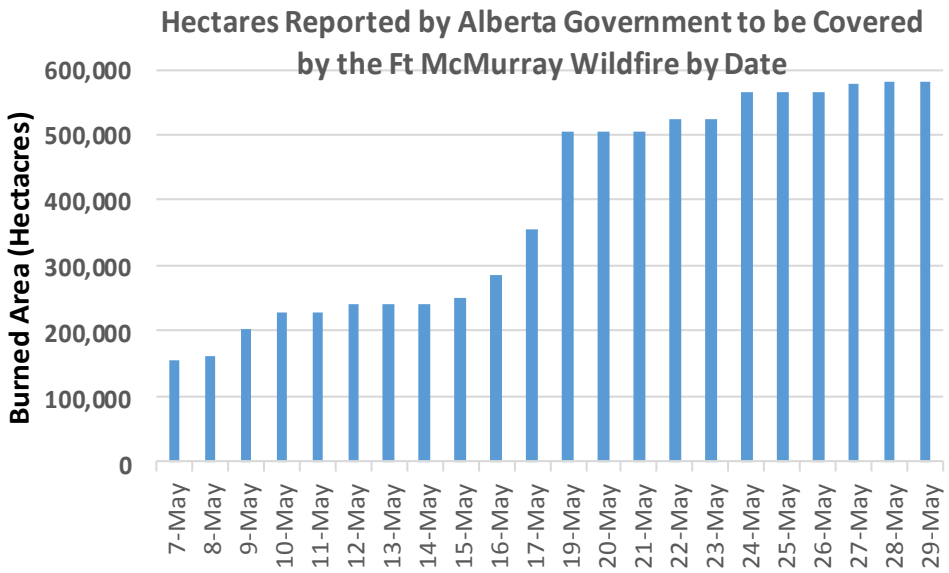


Figure 43. Hectares burned reported by Alberta Government by the Fort McMurray wildfire.
There is a sharp increase in the fire size between May 17 and May 20, leading to an increase in emissions in that time period. No data was available for May 18, 2016

Q is the total daily emission rate in tons per day of reactive hydrocarbons and nitrogen oxides. EPA recommends in the exceptional events guidance that only 60% of the hydrocarbons should be considered reactive. Therefore the reactive hydrocarbon emissions become rHC = 0.6 * Ehc or 0.6 * 44,182 = 26,509 tons of reactive HC emitted during the period of interest. No adjustments are suggested for the NOx emissions. Therefore the total rHC and NOx emissions over the period are 26,509 + 7,364, or 33,873 tons over the four days. On average this results in a daily emission rate, or Q, of 8,468 tons per day. However, data from Alberta shows that most of these emissions came over 2-3 days, (May 17 to May 19). A more reasonable estimate is 33,873/2.5 = 13,549 tons per day.*

*No fire size estimate was provided for May 18 by the Alberta Government site.

3.3.2. Estimate of d

Based on the large distance, there will not be individual analyses completed for each monitor in Maryland but an estimate of the distance from the Fort McMurray fire to the most distant monitor in Maryland will be calculated. This will supply a conservative yet representative distance the smoke traveled to the Maryland ozone network. A value of 3,280 km was therefore used for d, the flight distance from Fort McMurray to the Blackwater NWR monitor, near Cambridge, MD on the southern eastern shore.

3.3.3. Q/d Estimate

Using the values determined above, Q/d becomes 13,549 tpd divided by 3280 km or 4.1 tpd/km (Table 4). This value is well below the EPA recommended level of 100 tpd/km indicating clear causality. If instead we aggressively assumed the out of control fire consumed most of its fuel between May 17 and May 21 in one day's time, Maryland's Q/d value climbs to 10.3. Still well below 100. This assumes, however, no contribution of other fires in Canada or from other fires in Mexico which may have also mixed in with the plume across the Mississippi River Valley.

Table 4. Q/d analysis for various scenarios.

ACRES	Ehc (tons)	Enox (tons)	Q (tons)	No. days burning	d (km)	Q/d	DESCRIPTION
368,187	44,182	7,364	33,873	2.5	3280	4.1	Standard Q/d
368,187	44,182	7,364	33,873	1.0	3280	10.3	If the entire area burned between 5/17 & 5/20 burned in one day
368,187	45,000	3,000	48,000	1.0	3280	14.6	Comparing the Wallow Fire emissions to Fort McMurray; No Ehc adjustment
368,187	265,095	44,182	203,239	2.5	3280	24.8	Fuel loading at a maximum of 60 tons/arce instead of 10
368,187	265,095	44,182	203,239	1.0	1735	117.1	Maximum fuel loading, 1-day burning, with plume impacting Minneapolis, at MN

Taking a slightly different approach MDE considered the basis for the EPA guidance and look at emissions from one of the four fires EPA relied on in developing their guidance. Appendix A2 of the EPA Exceptiona Guidance Document indicates that EPA based their conclusions on 12 km grid CMAQ modeling of four 2011 multiday fires: Wallow, Waterhole, Big Hill and Flint Hills. Emissions from the fires were based on a program called SMARTFIRE. Using information available on the Wallow Fire, MDE approximated the emissions that might be calculated for the Fort McMurray fire.

The Wallow Fire was located in eastern Arizona and western New Mexico from May 29, 2011 through July 8, 2011 and burned 841 square miles (538,240 acres) by June 26th. The maximum daily emissions from that fire were reported as approximately 15,000 tons of rVOC and 1,000 tons of NOx. [Simulating Fire Event

Impacts on Regional ozone and $PM_{2.5}$ and Looking Forward Toward Evaluation, Kirk Baker, EPA October 5, 2015 and Using SOAS and related field study data for scientific and regulatory modeling, Kirk Baker, EPA, undated; both are slide presentations] If this fire were scaled up by a factor of three to approximate the total acreage burned in the Fort McMurray fire, then the daily emissions were as high as 45,000 tons for rVOC and 3,000 tons for NOx. These emissions produce a Q of 48,000 tpd and Q/d becomes 14.6 for Maryland – still well below EPA expectation for causality.

Taking a less conservative approach and recalling that a worst case fuel loading would increase our Q results by a factor of six, Q/d would in this case result in ~25 tpd/km; better, but not up to EPA's threshold of 100 tpd/km. While this approach might be justified by the ongoing smoldering of the peat and/or the intensity of the Fort McMurray fire, variability in the burn rate and other factors make it difficult to justify the fuel load increase without further details that may only be obtained through estimates which introduce their own error.

An ozone exceedance occurred in Minnesota on May 21, 2016. This location was only 1735 km away from the Fort McMurray fire source. It was not unreasonable to assume that 368,000 acres may have burned in approximately one day given the out of control nature of the fire. Without a size assessment on May 18, there was no way to discount this. It was also not inconceivable that the fuel load was closer to 60 tons/acre due to the ravage nature of the fire. Under these assumptions (i.e., assuming the entire area burned in one day with maximum fuel load), the Q/d value increases to 117 tpd/km in Minneapolis, MN. This would indicate that where the smoke precursors subsided to the surface with conducive local conditions (warm, sunny), ozone did respond with increased Q/d analysis over 100 tpd/km. Additionally, no contribution from sporadic but numerous wildfires across southern Saskatchewan were added to this analysis, which could bring the Q/d analysis even further above 100 tpd/km without making any liberal assumption of the emissions. The implications for Maryland are that the upstream airmass was ozone conducive and showed a clear causal relationship to the fire, meeting the EPA threshold of 100 tpd/km for Q/d analysis and was producing ozone due to the smoke before entering Maryland. Furthermore, due to the lofted nature of the smoke to the free atmosphere, it may be possible for precursors to not react as quickly as lower-level transport cases establishing the 100 tpd/km threshold such that 100 tpd/km is not representative of Canadian wildfire cases impacting the US. In Minnesota, May 21, 2016 was the highest ozone and the only exceedance for the entire 2016 season for that state. Such findings satisfy both Key Factors 1 and 2 in the EPA Exceptional Events Guidance and further suggest the smoke plume's impact on Maryland was exceptional in nature.

EPA guidance states that *"If the Q/d value compares favorably to analytical data from other fires, then the fire can be presumed to have had a causal effect on ozone concentrations at the point of concern."* Since 2015, at least three major Canadian wildfire episodes have impacted Maryland: June 9-12, 2015 (as thoroughly described in Dreessen et al., 2015); May 25-26, 2016; and July 20-22, 2016. Thus, by EPA's Q/d definition, MDE now has a small subset to compare other wildfire impacts on ozone within the contemporary emissions environment. A Q/d analysis for July 2016 is done in that exceptional event analysis. For June of 2015, Q/d was calculated using values in Dreessen et al., 2016, which listed 77,000

acres burned in a two (2) day period and smoke transported 3100km from central Saskatchewan. Dreessen et al., 2016, goes on to show the impact of the smoke plume as it descended on the eastern Midwest and Mid-Atlantic on June 9-11, 2015 and showed clear wildfire signatures and influences on ozone. Based on that research, Q/d for that ozone episode would have been 1.1 (Table 5). The May event demonstrated here had a Q/d four times as large (4.1). The July 2016 event had a Q/d of 1.8. Some research has noted the uncertainties in the influence of wildfire emissions in terms of strength and composition on ozone production (e.g., Hu et al., 2008). Thus it is quite plausible the value of 100 for Q/d is not relevant for long-range transport cases. It appears a more appropriate Q/d number for Canadian wildfire smoke transport cases to Maryland is closer to one (1), 100 times lower than the EPA suggested value. As the May 25-26 ozone event had a Q/d value which compared favorably with other fire events in Maryland, MDE believes this shows a clear causal relationship between the ozone and smoke.

Table 5. Q/d Analysis for three Canadian Wildfire events impacting Maryland.

ACRES	Ehc (tons)	Enox (tons)	Q (tons)	No. days burning	d (km)	Q/d	DESCRIPTION
368,187	44,182.00	7,364.00	33,873.20	2.5	3280	4.1	Fort McMurray - May 2016
271,134	32,536	5,423	24,945	4.0	3530	1.8	Northwest Territories - July 2016
77,000	5,544.00	1,540.00	7,084.00	2.0	3100	1.1	Lac La Ronge - June 2015

Noting the wide variability in emissions estimates from different approaches, and as the Q/d method does not generally satisfy the expectation of a clear causal impact, other evidence is presented demonstrating that the smoke plume from the Fort McMurray fire caused elevated ozone levels in Maryland.

3.4. 99th Percentiles

As part of demonstrating a clear causal relationship between ozone concentrations and the fire event, monitored concentrations were put in the context of historical observations. Observations at monitors falling at or above the 99th percentile in the past five years establish statistical evidence that the event was likely influenced by an exceptional event and are a "Key Factor" used to determine whether a Tier 2 application is appropriate. Following the Exceptional Events Guidance, the 99th percentile was calculated for all Maryland monitors for all days of the ozone season (April – September) from 2012-2016. Additionally the 99th percentile was calculated for all days of the ozone season excluding 2012, and all days of the month of May 2012-2016 to account for the rapid emission changes ongoing across the eastern US. These percentiles have been presented previously in scatter plots in Figures 19-34 and summarized in section 3.1 Historical Concentrations. For convenience, a summary table with comparisons of all the 99th percentiles is given in Table 6.

.

Table 6. 99th percentile values and comparisons to observations on May 25 and 26, 2016.
The 16 Maryland monitors for which MDE is seeking exclusion of exceptional event influenced have their 99th percentiles presented based on data from April 1 – September 30, 2012-2016, only 2013-2016, and only May 2012-2016. The final 6 columns highlight which monitors exceed their 99th percentile level ("YES") for a given data set and day (May 25 or 26). Blanks indicate the monitor did not meet the 99th percentile for that dataset.

		99th Percentile [ppm]			May 25, 2016			May 26, 2016		
Name	AQScode	All Data	No 2012	May Only	All Data	No 2012	May Only	All Data	No 2012	May Only
Aldino	240259001	0.0790	0.0768	0.0750		YES	YES		YES	YES
Beltsville CASTNET	240339991	0.0820	0.0743	0.0720		YES	YES			
Blackwater NWR CASTNET	240199991	0.0725	0.0680	0.0719				YES	YES	YES
Calvert	240090011	0.0769	0.0710	0.0736					YES	YES
Edgewood	240251001	0.0800	0.0790	0.0747			YES		YES	YES
Essex	240053001	0.0780	0.0750	0.0728	YES	YES	YES	YES	YES	YES
Fair Hill	240150003	0.0831	0.0799	0.0778		YES	YES			
Furley	245100054	0.0744	0.0724	0.0731	YES	YES	YES	YES	YES	YES
Glen Burnie	240031003	0.0770	0.0770	0.0757						YES
Horn Point	240190004	0.0772	0.0670	0.0715		YES			YES	YES
HU-Beltsville	240330030	0.0780	0.0720	0.0740		YES			YES	
Millington	240290002	0.0830	0.0729	0.0751	YES	YES	YES		YES	YES
Padonia	240051007	0.0800	0.0760	0.0750				YES	YES	YES
PG Eq Cntr	240338003	0.0809	0.0737	0.0714		YES	YES			
S. Maryland	240170010	0.0771	0.0726	0.0709					YES	YES
South Carroll	240130001	0.0739	0.0700	0.0709		YES	YES	YES	YES	YES

3.5. Evidence that the Fire Emissions Affected the Monitors

3.5.1. Evidence of Fire Emissions in Maryland

Wildfires produce both primary and secondary pollutants which may be utilized to track the impact of smoke downstream from the fire source. While satellites may be able to track smoke plumes over wide areas and easily track their transport, they do not necessarily confirm the existence of smoke at the surface by themselves. The MDE monitoring network observes total $PM_{2.5}$ mass and speciated compounds such as ionic potassium (K+) and organic carbon (OC), as well as other pollutants like CO and NOx, which can act as tracers of wildfire emissions. Analyses of these various species which can be attributed to wildfires are here presented. The analyses show the ozone episode in Maryland was characterized by enhanced concentrations of wildfire species. Unfortunately, the specific days of interest in Maryland (May 25 and 26) did not fall on 1 in 3 run speciation days. However, enough influence of the fire was seen both upstream and lingering in Maryland on May 24 and 27, 2016 to clearly demonstrate the surface air was impacted by wildfire smoke.

3.5.2. Particles

$PM_{2.5}$ can be both a primary pollutant and a resultant secondary pollutant of wildfire emissions downstream as photochemistry within the plume converts certain species to aerosol. The entire MDE network showed a correlated increase in $PM_{2.5}$ 24-hour averages from May 24 –29 which aligned with the onset of the smoke plume in Maryland (Figure 44). No other period of the month exhibited such a coherent increase across the entire Maryland network. Though the late May period did not possess the highest particle observations of the month, it did exhibit the highest distribution and highest-low observation for the entire month. The fine particle observations therefore provided additional evidence that along with ozone and ozone precursors, fine particles were transported within the smoke affected airmass and were a distinct indicator of wildfire emissions, particularly since speciated particles associated with wildfire emissions showed similar increases.

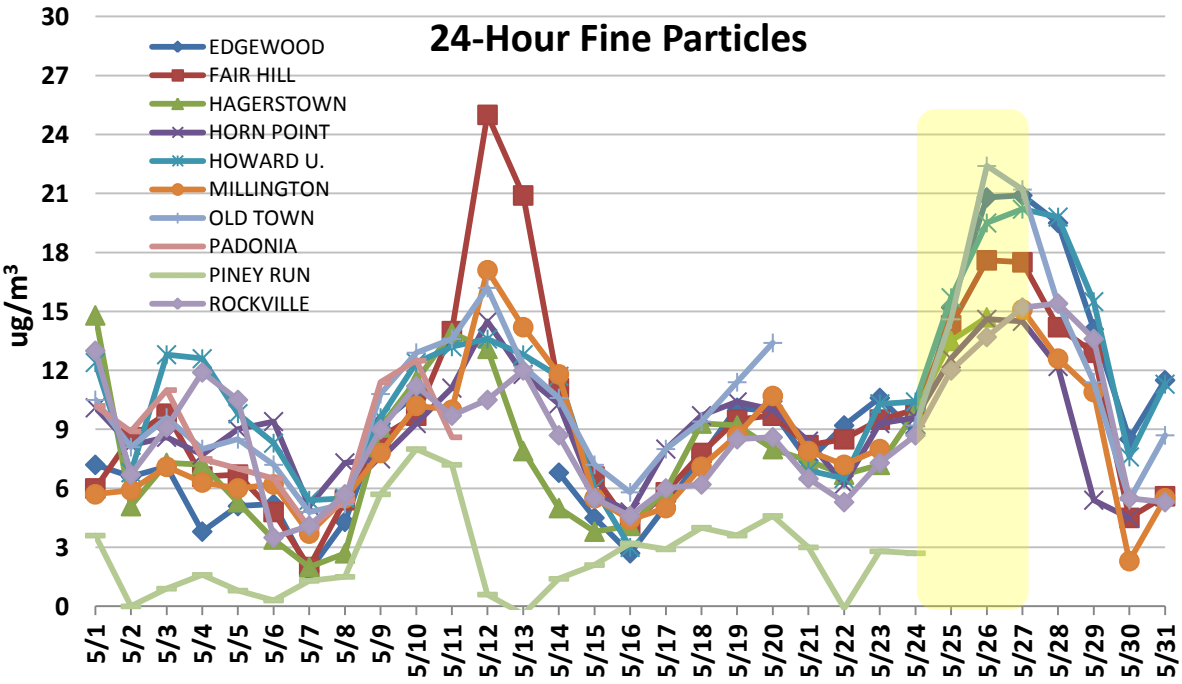


Figure 44. Daily averaged fine particle (PM2.5) concentrations for all sites available in Maryland for the month of May, 2016. The smoke influence as defined by the HMS analysis described in the conceptual model of this document is highlighted by the yellow shading from May 24-27.

3.5.2.1. Potassium Ions and Organic Carbon

Particle pollution generated from biomass burning is typically dominated by organic carbon (OC) and black carbon (BC; Martins et al., 1998), and possesses ions such as potassium (Lee et al., 2010). Ionic potassium (K^+) acts as a useful tracer of wildfire smoke because there are few anthropogenic sources, and concentrations above background levels are a signature of wildfire emissions. MDE's 1 in 3 sampling days missed the exceedances on May 25 and 26 (no speciation data on the day of the exceedances). However, the speciation samples did bracket the event on May 24 and 27 and evidence presented here-in has

displayed that some initial smoke influences began on May 24 and persisted in to May 27 in Maryland. The samples collected showed concentrations of K+ and OC were amplified in late May indicating wildfire smoke presence in the surface air across Maryland (Figure 45). K+ mass during the May ozone event was not the highest in April or May, but was still elevated and the quantity of ions were nearly identical on May 24 and May 27 at both Essex and HU-Beltsville monitoring sites clearly demonstrating a uniform pollutant load of potassium across Maryland. This is unlike other days which might have been higher but only at a single monitor. OC mass was the highest for both monitors in late May, coinciding with the smoke event which was a clear indicator of wildfire influence. The highest concentrations were on May 27, the day after the highest, most widespread ozone day in Maryland of 2016. In the present study, only the fringes of the most significantly affected air were sampled on May 24 and May 27. Additionally, transport of the photochemically aged airmass took upwards of five days to reach Maryland. Regardless, the data of these smoke tracers show a temporal maximum bracketing the ozone exceedance in Maryland. These pollutants provide a heavy weight of evidential support of the presence of smoke at the surface during this exceptional ozone event.

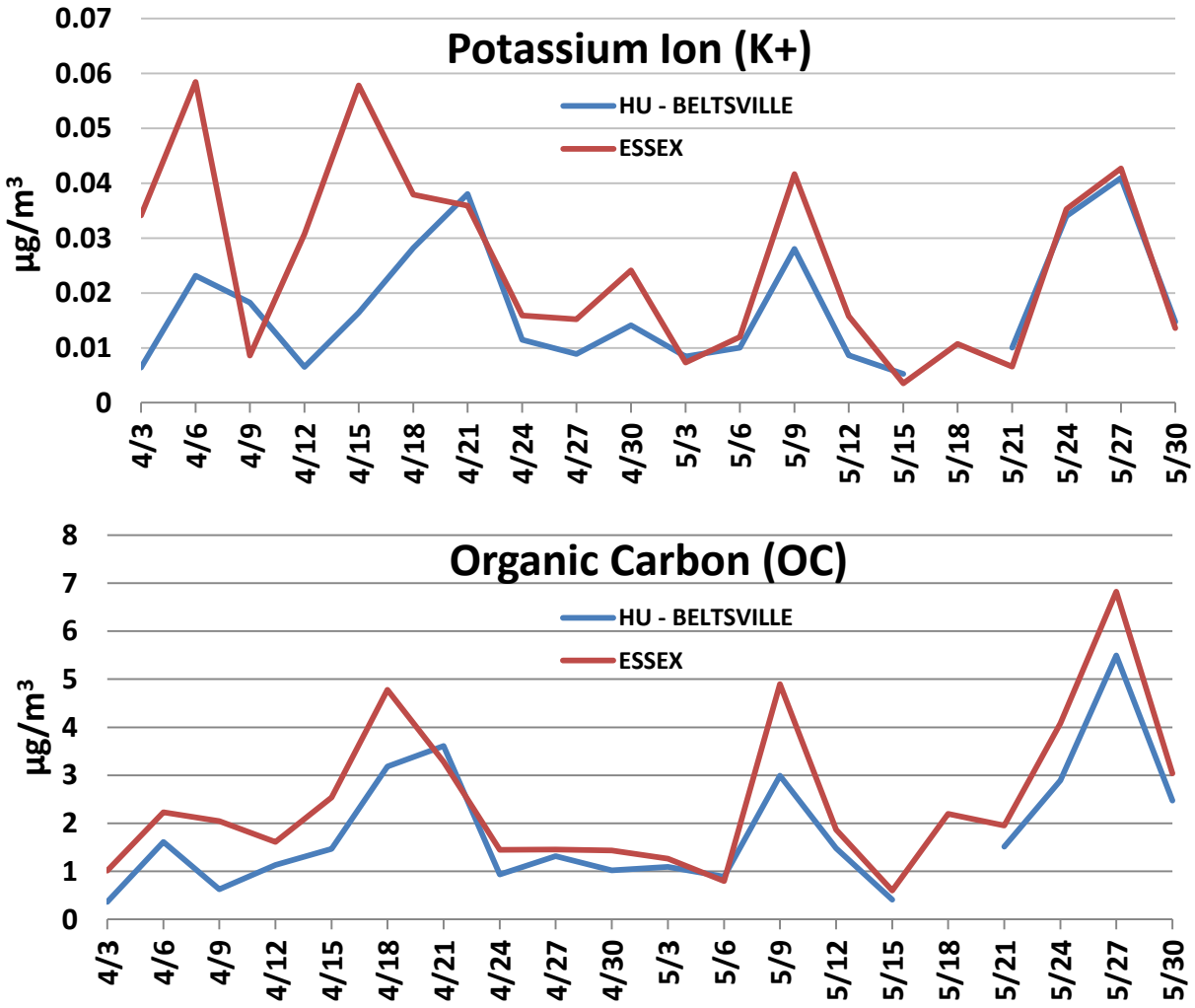


Figure 45. (a) Potassium Ion and (b) Organic Carbon, sampled every third day, from April through May of 2016.

The two sites shown are Essex and Howard University (HU) Beltsville. Potassium Ions during the May ozone event were not the highest in the two months shown, however, the quantity of ions were nearly identical on May 24 and May 27 at both sites, suggesting uniform pollutant load of potassium across the region. Organic Carbon mass is the highest for both months in late May, coinciding with the smoke event. The highest concentrations were on May 27, the day after the highest, most widespread ozone day in Maryland of 2016.

3.5.3. Carbon Monoxide (CO)

CO has been previously identified as a wildfire smoke indicator, can play a role in ozone production, and followed similar trends to other pollutants over the lifetime of the event (Figure 46). Essex, HU-Beltsville, and the Howard County (HoCo) Near Road sites all had the highest CO concentration of the entire month of May on May 25 and 26. To a lesser extent, other monitors (Piney Run and Horn Point) showed an increase in CO as well, though recall these sites were less impacted by the smoke plume than the more northern and eastern monitors in Maryland. The increase in CO at Essex and HUB coincident with increased wildfire particle species and increased concentrations of ozone observed aloft provided irrefutable evidence for the direct impact of the smoke at the surface. Consistent with these surface observations were total column CO retrievals from satellite generated via Giovanni Data (https://disc.gsfc.nasa.gov/ Figure 42). The satellite showed a plume of enhanced CO starting over Canada meandering southeastward across the Great Lakes in line with the time frame outlined in the conceptual model (see section 2). The plume arrived over Maryland in agreement with the increased CO concentrations at Maryland surface monitors (Figure 46). Together, these observations indicated that wildfire-related ozone precursors were present to contribute to ozone production upstream across the Midwest and then moved into Maryland by May 25.

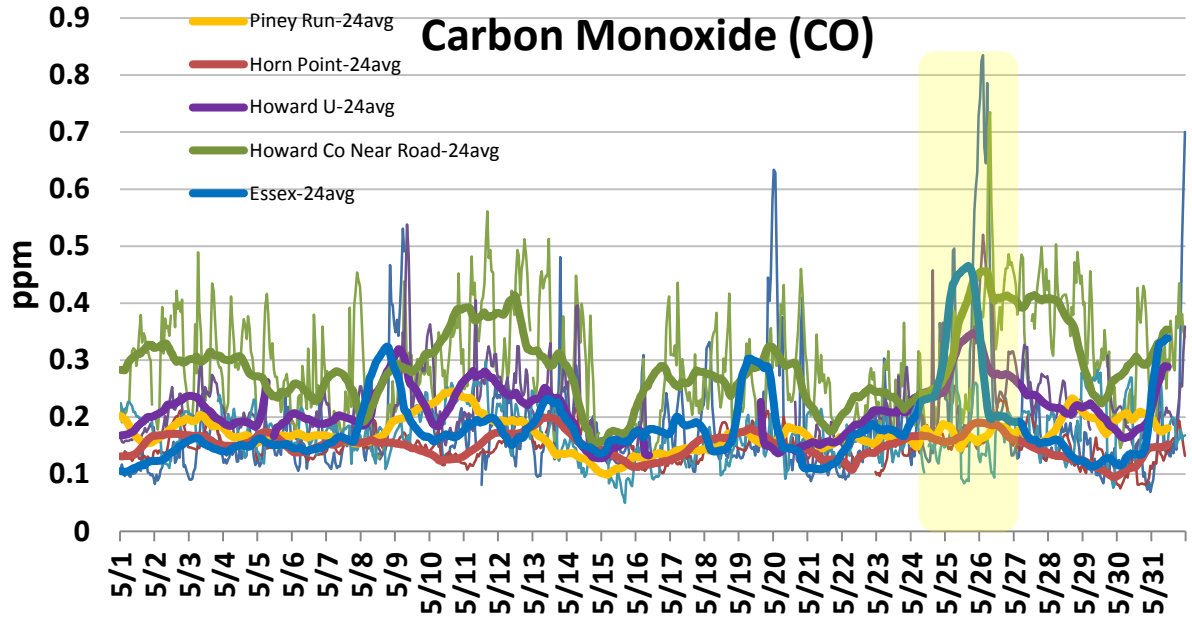


Figure 46. Hourly Carbon Monoxide (CO) overlaid with a running 24-hour average at five sites in Maryland. The smoke event is highlight in yellow. "24avg" indicates the thick lines drawn are a running 24-hour boxcar average of the underlying hourly data, given as fine lines of the same color in the time series.

3.5.4. Nitrogen Oxides

Singh et al. (2012) showed that ozone production rates from wildfires in California were dependent upon available NOx (NOx = sum of nitrogen oxide (NO) and nitrogen dioxide (NO_2)) and that NOx from the fires themselves was relatively low. However, NOx emissions from fires can vary greatly and research has noted the uncertainties in the influence of wildfire emissions from one to another (e.g., Hu et al., 2008). In the current study, the monitors observing the highest ozone concentrations were near urbanized areas on May 21 (Minneapolis) and May 23 (Memphis, St. Louis, Indianapolis, Detroit) suggesting the local NOx contributions from these areas was partially responsible for ozone concentrations in those areas. However, it was likely that the urban areas simply augmented ozone production within the smoky airmass, since ozone concentrations within the smoke plume were already increasing in non-urban areas. Said another way, ozone would not have reached the MD8AO concentrations observed during the event without the presence of the smoke. The smoke augmentation of ozone was particularly likely and apparent given the spatial coherence on May 23 of the entire corridor of HMS analyzed smoke with enhanced ozone from the Great Lakes the Gulf Coast (Figure 18f). The reported incredible intensity (heat) of the Fort McMurray fires was likely to create NOx along with the VOCs within the smoke plume.

NOx emissions across the upstream region of Maryland were already shown to be the lowest on record in late May of 2016. However, as Dreessen et al. (2016) predicted as a result of the June 2015 case:

> "This [June 2015 smoke event] shows that the drastic NOx reductions across the [Ohio River Valley] may not be enough in future wildfire events and that future events [may impact NAAQS compliance]."

Said another way, an ozone exceedance was unlikely to occur in Maryland without the burden of smoke on the airmass. As the smoky airmass aged, photochemical reactions within the plume made it "ozone-ripe", creating an airmass easily augmented even by minimalistic NOx contributions. Then as suggested by Dreessen et al. (2016), the additional NOx, either traceable to the fire source itself or any anthropogenic source, was stored within the smoke plume via the abundance of VOCs. Hourly NOx observations from May 24 – 26 had a peak in concentrations at available monitors in Maryland which was higher than any other day in the month (Figure 47). Both near-road sites, Essex, Oldtown and Piney Run 24-hour running average concentrations rose during this time period with only Piney Run not achieving the highest running average of May 2016. Local emissions of NOx surely played a minor role in augmenting ozone concentrations in Maryland as urban pollution mixed with the smoky, ozone laden airmass, as earlier stipulated. However, CO, particle mass, and particle speciated compounds all suggest a significant wildfire presence in the dirtied upstream airmass. The ozone precursors already within the plume fostered ozone production at levels not otherwise feasible in the contemporary emissions environment.

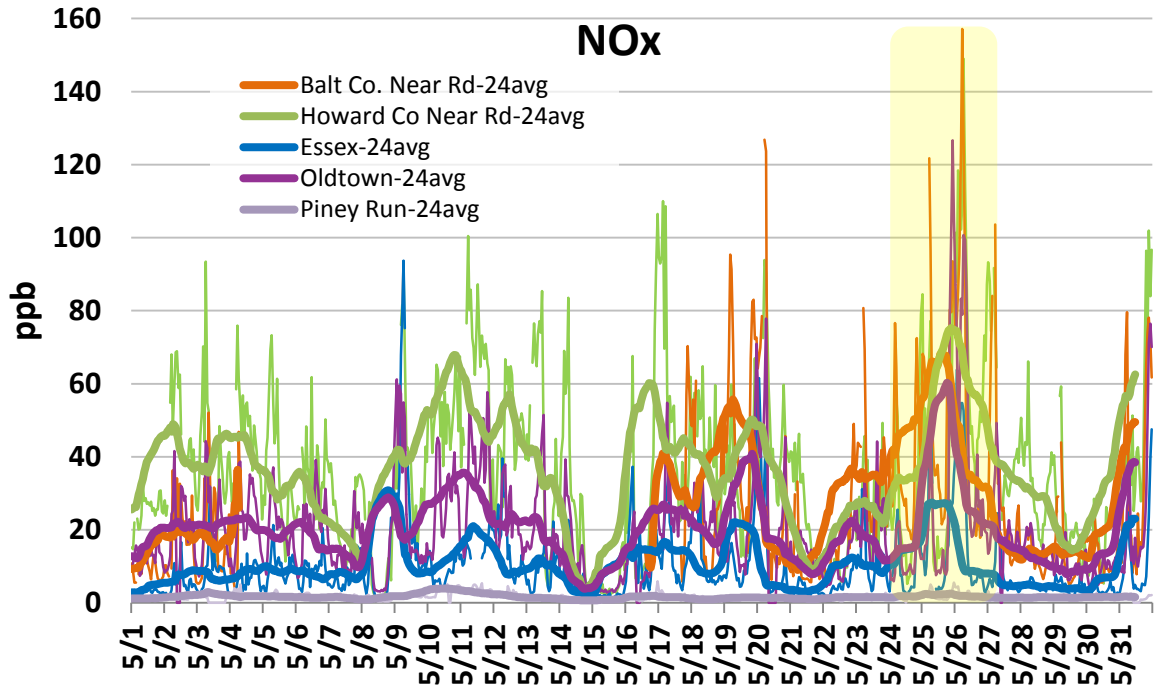


Figure 47. As in Figure 46 except for nitrogen oxides (NOx) from available Maryland monitors in May, 2016.

3.5.5. NOx Historical Context: Local May NOx, Aged Nitrogen and Total Reactive Nitrogen

If NOx was excessively stored within the smoke plume due to the abundance of VOCs as discussed in Dreessen et al (2016), strong evidence of aged NOx would be present. Further study of the composition of the Nitrogen in the airmass showed that the total active nitrogen (NOy) was both one of the largest NOy observations in May in the past five years (Figure 48a) and that total NOx in May of 2016 was the also highest among the last 5 years (Figure 48b)despite the lowest EGU NOx emissions upstream to-date (Figure 5). Daily average NOx concentrations for all May days from 2012-2016 at Maryland monitors showed that late May of 2016 had some of the highest NOx observations at many of the monitors in the network over the entire period. Total reactive nitrogen (NOy) shows similar characteristics with the highest May reading from the past 5 years in late May of 2016, consistent with the time period of the smoke influenced airmass in Maryland. HU-Beltsville reported the second highest 24-hour average during the smoke event in May of 2016 compared to the entire 2012 – 2016 period. There was no doubt the airmass was characterized by abundant NOx not seen even when upstream EGUs were emitting larger amounts of NOx prior to the 2013-2016 era.

Subjective analysis of nitrogen species allows some qualitative source attribution. Generally it is difficult to distinguish NOx sources from each other (i.e., point, mobile, wildfire). Fresh NOx emissions tend to be dominated by Nitrogen Oxide (NO) rather than Nitrogen Dioxide (NO_2) or other non-NOx speciations (NOz). NO has a shorter lifetime due to its high reactivity, thus an airmass dominated by NO_2 and NOz tends to

indicate aged nitrogen emissions. The composition of the NOx was overwhelmingly composed of older NO_2 on May 25 and 26. In fact, the Essex monitor recorded the 6th and 9th highest daily average NO_2 for the entire 2016 ozone season (151 days) on May 25 and 26 (not shown). The high levels of NO_2 were indicative of an aged airmass, NOx transport and therefore non-local ozone. Unfortunately no NOz concentration was available during this time period. However, the substantial proportion of older NO_2 at Essex and Oldtown, along with the high concentration of NOy at the HU-Beltsville site all suggests older NOx emissions, transport and older ozone. MDE therefore contends the increased NOx observed during the ozone event was a result of efficient NOx storage within the smoke plume sourced from the fire itself and diminutive regional NOx contributions, both which caused NOy to be beyond contemporary concentrations in Maryland.

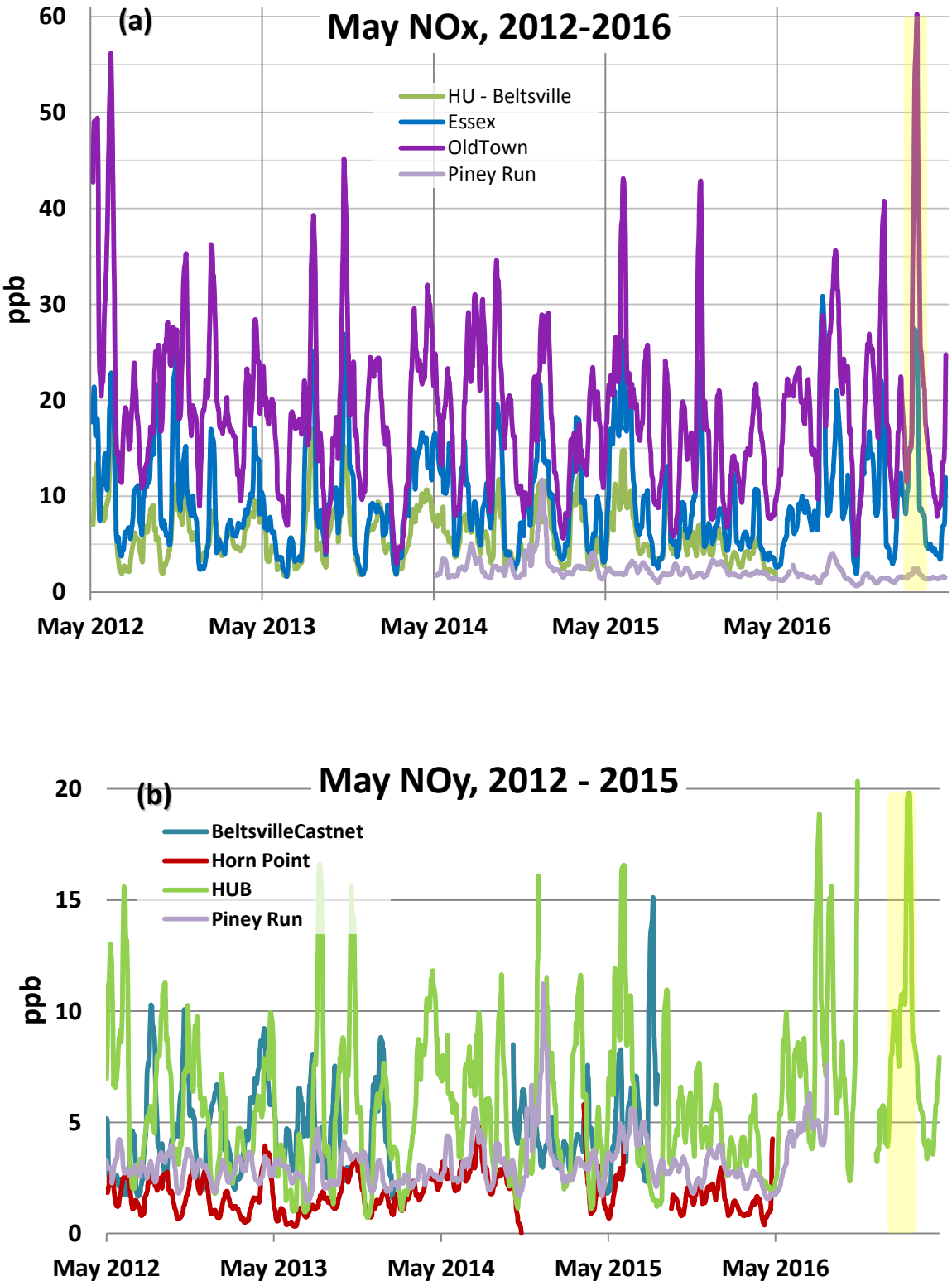


Figure 48. (a) NOx and (b) NOy for all available Maryland monitors for days in May from 2012 to 2016. The area in yellow highlights the 2016 smoke event on May 24-26. The only available NOy in 2016 was at the Howard University, Beltsville (HUB) monitor. Both NOx and NOy were higher than each May in the previous 5 years.

3.6. Analysis Methods to Assess the Smoke Impact

3.6.1. Ozone to NOx ratio

MDE has asserted the excess NOx and NOy observed in the Maryland monitoring network was either from the fire itself or due to excessive storage of NOx within the smoke plume due to excess reactive VOCs supplied by the smoke as suggested in Dreessen et al., (2016). To further evaluate whether the increased NOx observed was carried within the smoke plume and was not simply from upstream EGUs (a typical "non-event" exceedance characteristic), MDE generated an ozone to NOx ratio for the past seven years. In a NOx limited environment, less NOx means less ozone. Thus, an airmass characterized by an abundance of ozone but also impacted by copious EGU NOx emissions will maintain a low or constant ozone to NOx ratio. A reduction in emissions leading to reductions in ozone and again the ratio would remain relatively constant. However, an airmass producing abundant ozone without substantial increases in anthropogenic NOx emissions produces a high ratio and indicates a highly efficient, ozone-productive airmass composition. Such a scenario indicates additional influences on the airmass composition.

The ozone values on May 25 and 26, 2016 reached MD8AO concentrations seen previously only in years with twice the amount of EGU NOx emitted from Maryland, Pennsylvania, West Virginia, Northern Virginia and Ohio, the states(areas) from which same-day emissions would affect the ozone concentrations on May 25, 2016 based on backwards trajectories. As a result of the lower emission from these areas, the ozone to NOx ratio (maximum statewide 8-hour average concentration divided by total NOx output across these regions) reached the highest value ever seen in Maryland on May 25 and 26, 2016, suggesting ozone production was beyond the typical exceedance event production capacity and was likely aided by other constituents (Figure 49a). This supports the assertion that VOCs are effective at storing NOx in the smoke plume for later ozone development, regardless of absolute NOx output from the fire itself or point sources along the track of the plume as discussed earlier. As NOx was stored the ozone content in the plume also increased as the smoke plume aged. Thus despite the lowest May EGU NOx emissions ever observed, ozone production rose uncharacteristically high in the early ozone season. Therefore the high ozone concentrations must be due to smoke influenced ozone production.

MDE contends that the reason for the ozone exceedances in Maryland on May 25 and 26 was the advection of an airmass which was directly impacted by smoke for several days prior to moving into Maryland. Under the same assumptions above, areas upstream of Maryland should also indicate an airmass influenced by smoke and therefore have a high ozone to NOx ratio. The first wide spread exceedance day of the extended period was on May 23 across the Midwest and Great Lakes (see Figure 18). Ozone exceedances were at first isolated to urban centers where additional NOx was available to raise concentrations above the NAAQS threshold. Since mobile emissions are assumed relatively constant between workdays, emissions from sources such as EGUs must not change significantly between days to conclude that the smoke played the integral part in these exceedances. If the EGU NOx emissions were insignificant to ozone production across the Midwest as compared to the contribution to ozone supplied by the smoke, the ozone to EGU NOx ratio

should be quite high. If ozone production was dependent on EGU NOx output, the ratio would remain constant and/or low.

The NOx to ozone ratio in Indiana on May 23, 2016 was the second highest ever in May since 2010, and May 21-23, 2016 were three of the top 5 highest ratios of the entire data set with five of the top seven daily ratios between May 19 and 24, 2016 (Figure 49b). Using similar methodology to that used in Maryland, these ratios were calculated using emissions from Indiana, Ohio, and Michigan based on a 72-hour backward trajectory from Indianapolis, IN on May 23 (Figure 50). Interestingly, May 7, 2016, was a day also influenced by smoke (based on HMS analysis) and had the highest ratio in Indiana, though no exceedances occurred due to cool and wet conditions. This shows that the airmass developed ozone in an environment that was otherwise devoid of high levels of anthropogenic NOx relevant for abundant ozone concentrations in the absence of added smoke.

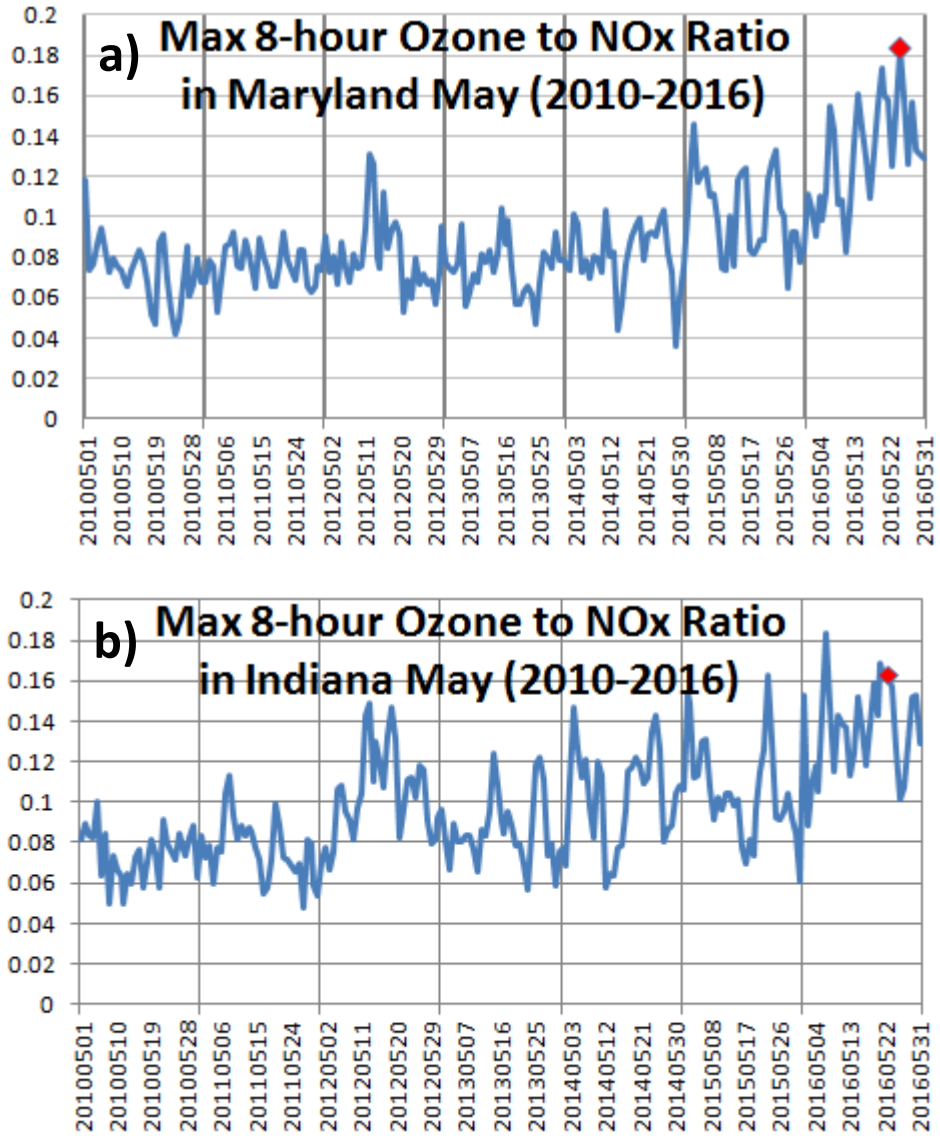


Figure 49. Ozone to NOx ratios for (a) Maryland and (b) Indiana.
The higher the ratio, the more ozone is created for a given amount of NOx output. NOx output used in each case is described in the text but is based on statewide emissions. States used were selected based on backward trajectories as described in the text. The red diamonds highlight the first day of an exceedance in each state.

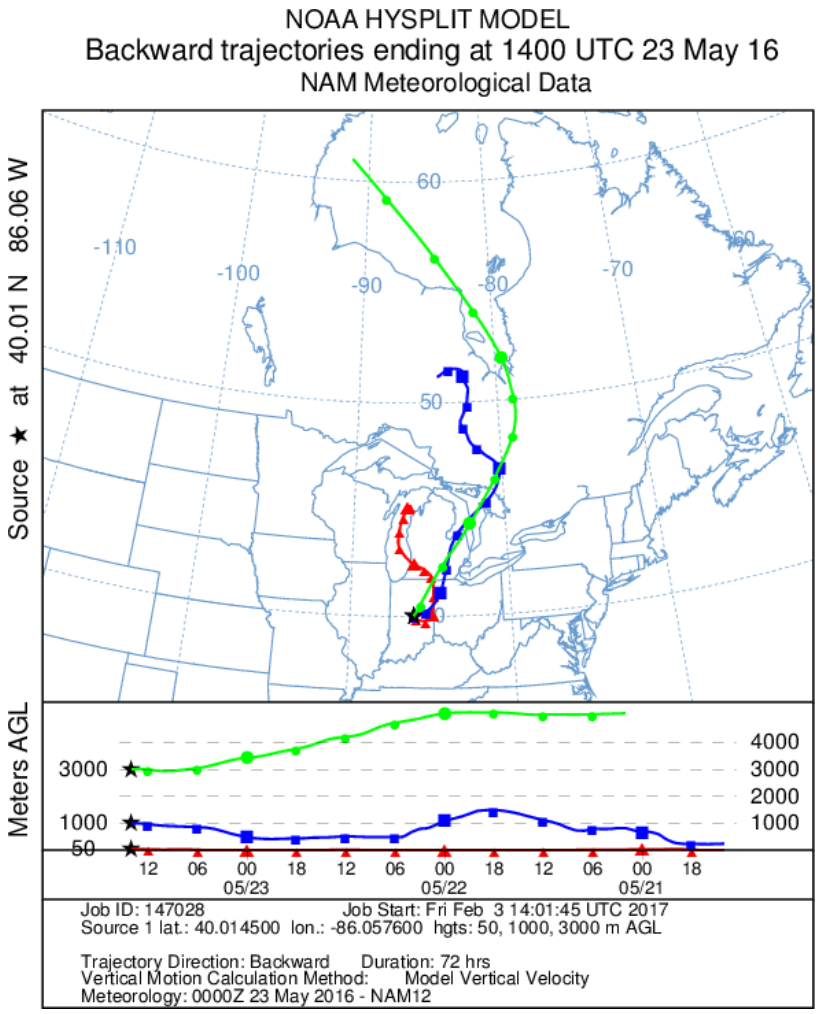


Figure 50. 72-hour backwards trajectory from Indianapolis, Indiana on May 23, 2016.

3.6.2. Model Data: CMAQ Underestimation of Ozone

The presence of smoke during the May 25 and 26, 2016 ozone exceedance days provided clear evidence that significant portions of ozone production were attributable to smoke. Given the presence of increased smoke tracers monitored at the surface and ozone values equaling or exceeding the 99th percentile when compared to ozone concentrations of the past 5 years, the impact of smoke constituents on ozone enhancement was incontrovertible. To quantify the attribution, MD8AO concentrations forecast with the operational National Ocean and Atmospheric Association (NOAA) Community Multi-scale Air Quality (CMAQ) ozone model were compared to observed MD8AO concentrations. Source information from the Fort McMurray fire as well as gas phase chemical interactions from wildfire smoke and their interactions with ozone were not included in the NOAA operational CMAQ model during 2016. Therefore, the NOAA operational CMAQ model represented a prediction of ozone in the absence of smoke and under normal conditions. The NOAA CMAQ ozone model reported approximately +7ppbv high bias and 15.1ppbv root

mean square error (RMSE) for June ozone predictions in 2010 (Chai et al., 2013) (i.e., it tends to slightly over-forecast ozone concentrations). The over prediction error has improved since 2010, but the model maintained a high bias in the Maryland area through 2016 (Figure 51). With this information in mind, the difference in the model forecast ozone to actual observations in July of 2016 provided an estimate of the increase in ozone due to smoke and the spatial extent of the influence.

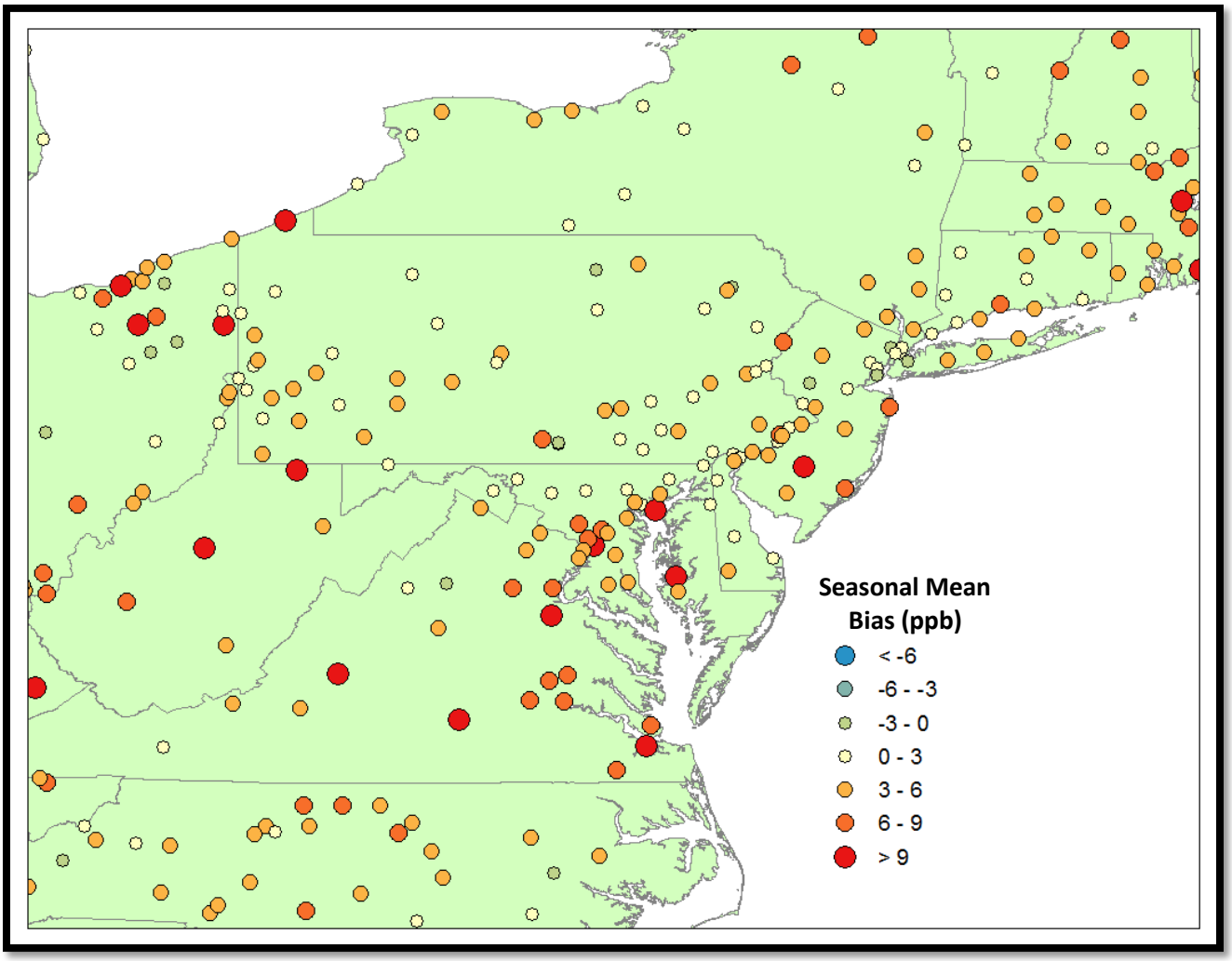
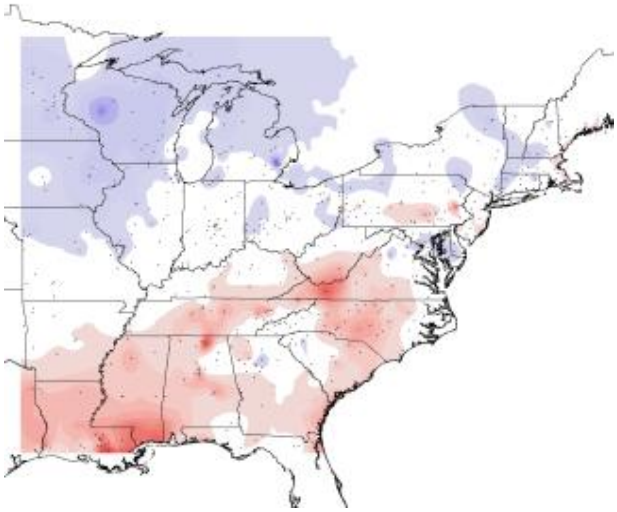


Figure 51. NOAA 2016 operational CMAQ ozone prediction errors at monitors across the northeast US.

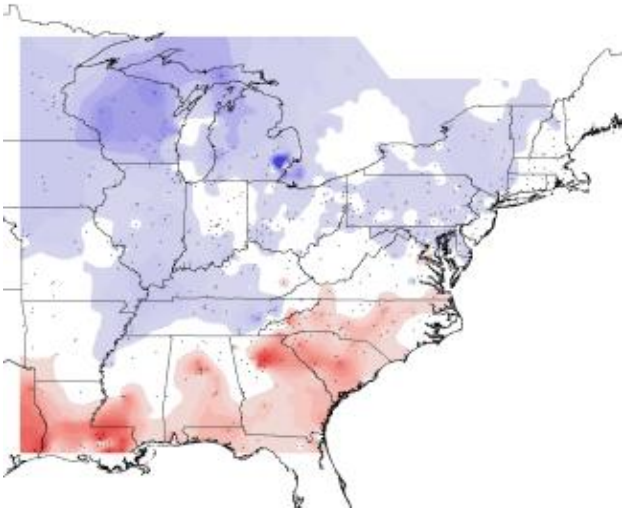
Gridded model data was extracted at observation points throughout the eastern CONUS for May 18 –28, 2016. The difference between the predicted and observed MD8AO were interpolated across the region on a daily basis and showed an area of model under prediction stretching from the upper Midwest on May 20 and 21, moving eastward to the northeast and Mid-Atlantic, to include Maryland, by May 25 (Figure 52). Cross referencing Figure 52 with Figure 18 showed similar patterns of smoke, ozone, and under-prediction by the NOAA CMAQ model. While the NOAA CMAQ model occasionally under-predicts ozone early in the season in the Mid-Atlantic, the model typically does not under predict by more than 10ppb. Since the NOAA CMAQ did not include 2016 wildfire emissions in the ozone chemical creation mechanism, under predictions

by the model were the result of fire emissions and ozone precursors which were not accounted for in the model input, leading to higher than predicted MD8AO. The underlying assumption then was that under prediction of MD8AO coincident with smoke to be caused by precursors within the smoke. It would be very coincidental for the model to under predict both quantitatively and spatially in line with the smoke plume. Sequential examination of the images reveals an area of modeled under prediction of magnitudes reaching >20ppb (dark blues) that moved through the upper Mid-West and Northeast, extending as far south as DC. The signal loses cohesiveness after May 26. The area of under prediction in the model closely correlates to the movement of ozone and HMS analyzed smoke plumes (compare Figures 52 and 18). This provides a quantitative measure of the impact of smoke during this event, suggesting the smoke provided anywhere from 5 ppb to over 20 ppb of additional ozone production on MD8AO values across the northeast US.

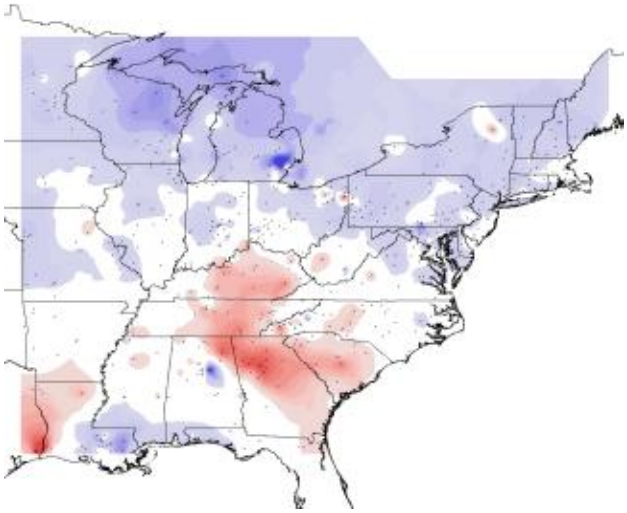
May 18, 2016



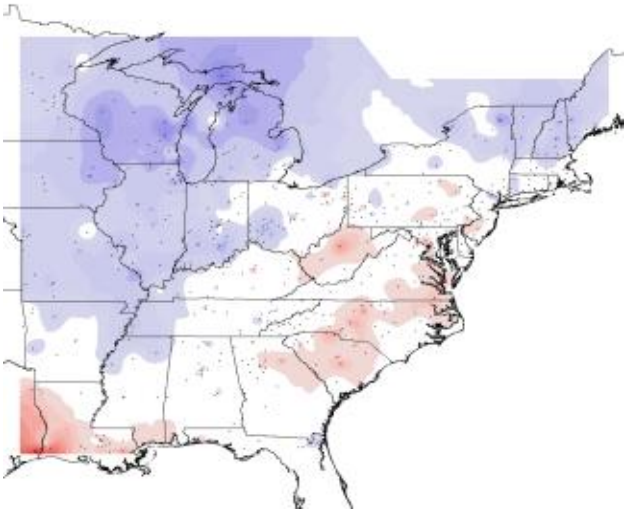
May 19, 2016



May 20, 2016

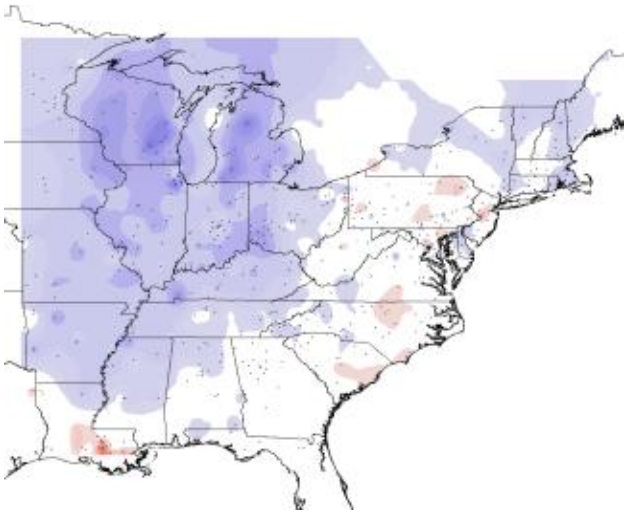


May 21, 2016

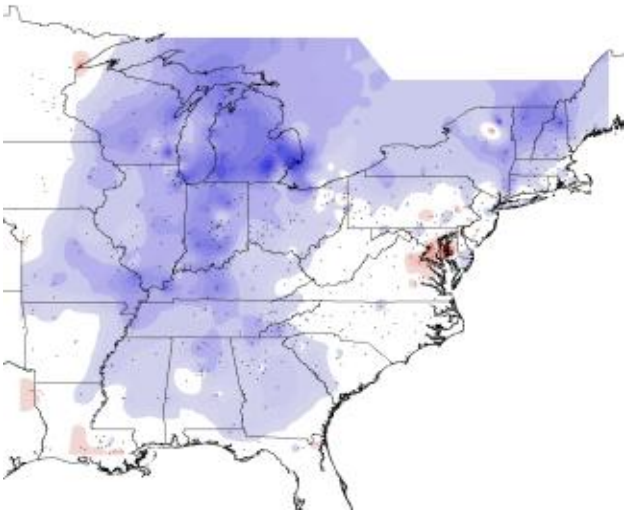


May 22, 2016

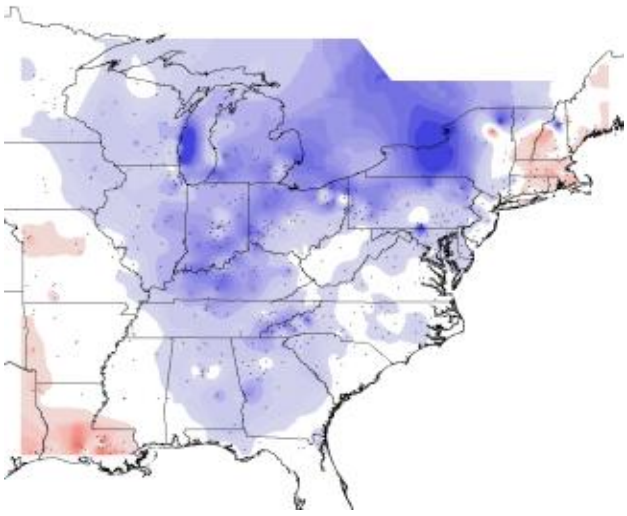
May 23, 2016



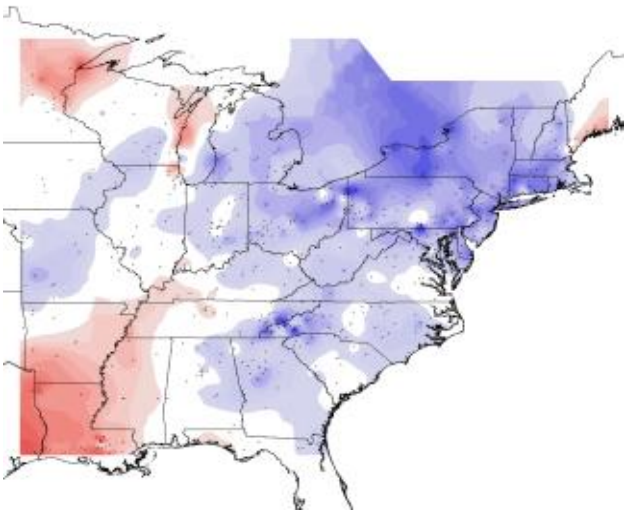
May 24, 2016



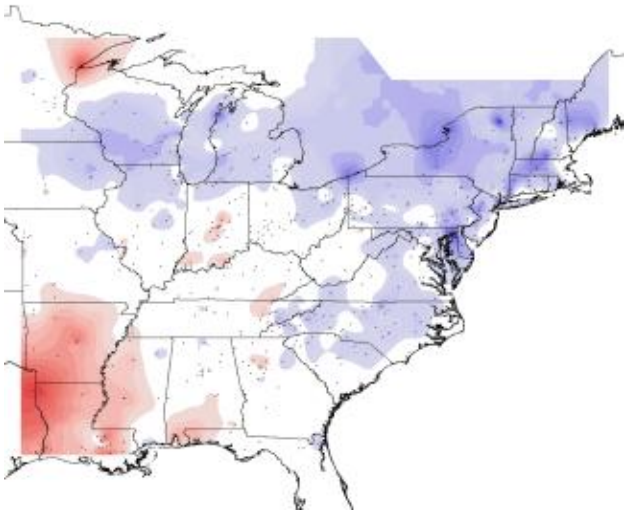
May 25, 2016



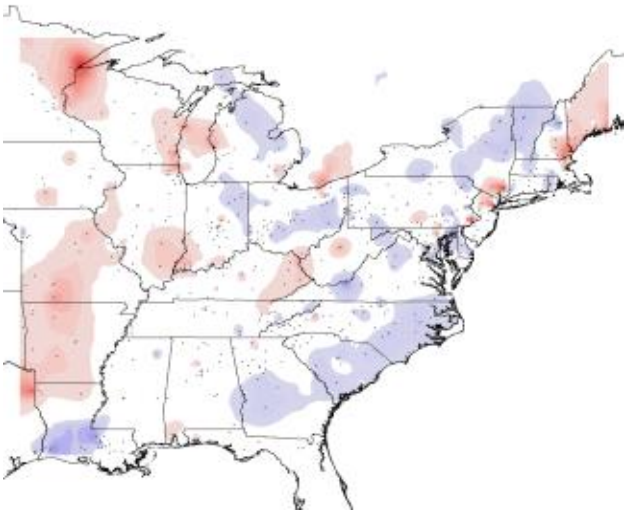
May 26, 2016



May 27, 2016



May 28, 2016



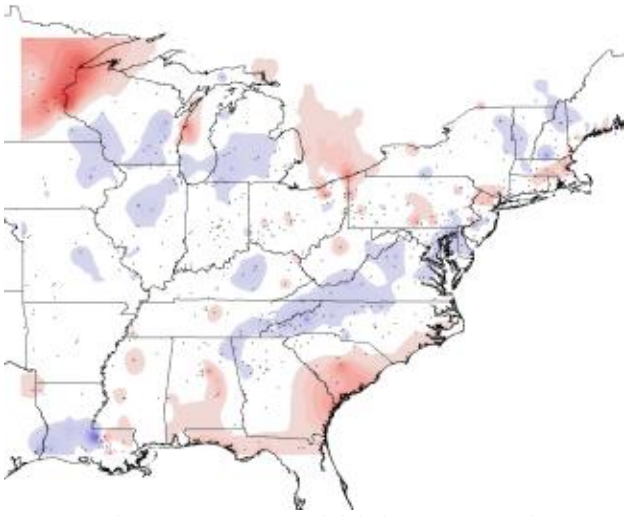


Figure 52. The NOAA CMAQ model daily maximum 8-hour ozone predictions for May 18-28, 2016 comparison to AQS observations for the entire eastern United States.
Colors represent operational NOAA CMAQ model predicted ozone minus observations contoured from May 18-28, 2016. Darker areas of blue show more significant model under prediction, while areas of darker red show areas of model over-prediction. Colors begin at +/- 5ppb error magnitude. Small black dots are locations of ozone monitors.

3.6.3. Spatial Tracking of Organic Carbon (OC) and Potassium (K+)

OC and K+ concentrations in Maryland were previously shown to be elevated on the periphery days of the exceedance event. Speciated data (run every 3 or 6 days) retrieved from several states showed an area of increased concentrations of both species moving west to east across the upper Midwest from May 21 to May 27, consistent with the track of the smoke plume analyzed by HMS (Figure 53). Particularly on May 24, the magnitude and spatial extent of OC and K+ was greatest across the Great Lakes (the states of Michigan and New York) which was centered on the area of greatest 8-hour ozone concentrations and the area previously described as influenced by the Fort McMurray wildfire smoke. Since the K+ and OC are specific wood combustion markers these speciated $PM_{2.5}$ data provided conclusive evidence that the ozone affecting the upstream airmass of Maryland developed in areas under the heavy influence of smoke related emissions. More specifically, these wildfire markers were found in areas with high ozone production and concentrations concurrent with the intense under prediction by the NOAA CMAQ model, all which point to a wildfire smoke influence on ozone concentrations. Previous analyses demonstrated how this smoke influenced air was transported into Maryland.

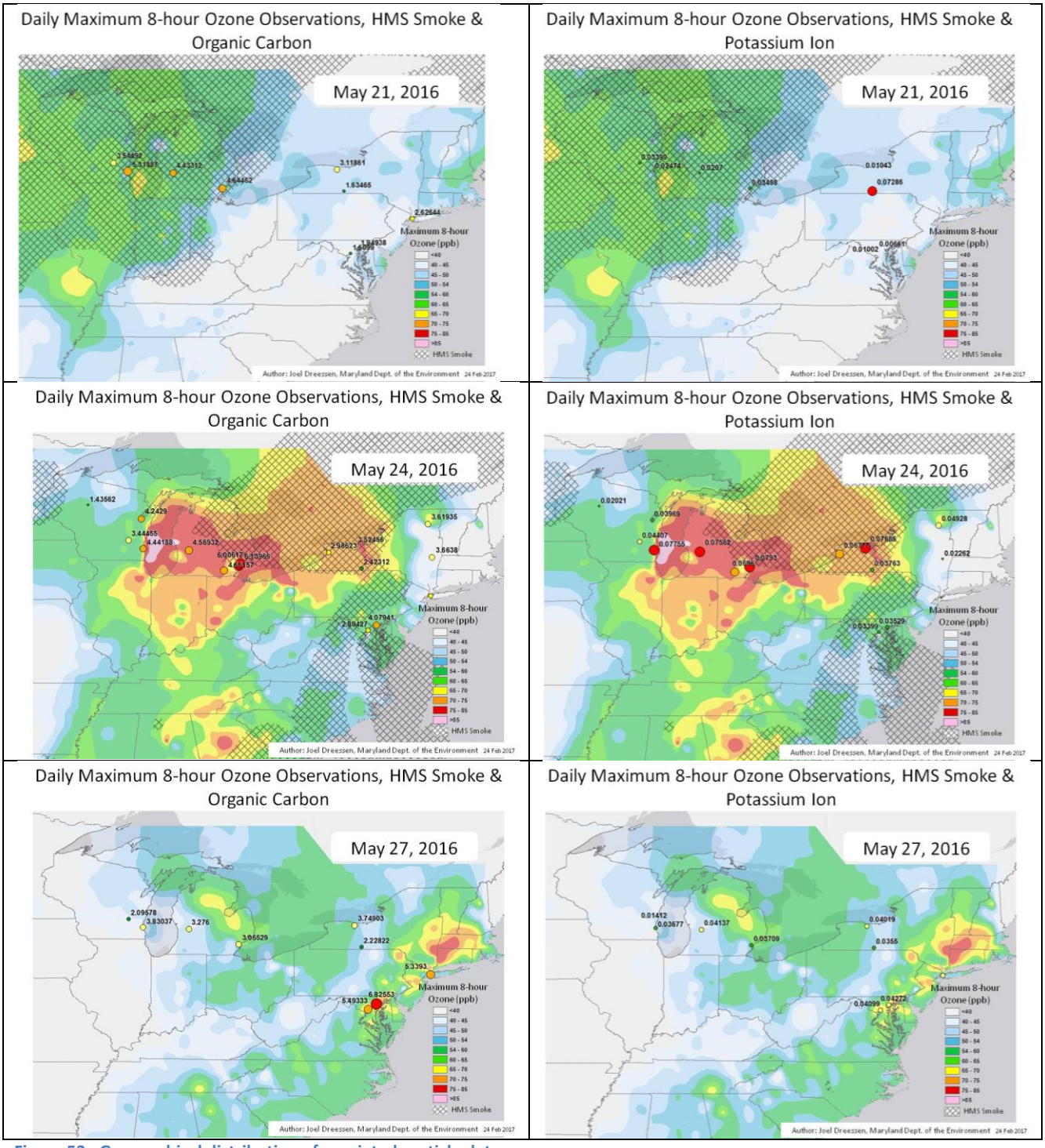


Figure 53. Geographical distribution of speciated particle data.
Data was plotted at available monitors and overlaid on contoured MD8AO concentrations and HMS analyzed smoke for May 21, 24 and 27.

3.7. Similar Day Analysis

Similar meteorology in the absence of smoke should not produce ozone exceedances in Maryland as was observed on May 25 and 26, 2016. To address this, a similar day analysis attempts to identify days which are similar in pattern and characteristics (temperatures, winds, transport regime) but without the burden of smoke on ozone production. A comparison of such days should yield substantially less ozone at monitors when not impacted by smoke.

To better establish the transport pattern for the onset of the event for a similar day analysis, the radar wind profilers (RWP) at Piney Run and Horn Point were examined (Figure 54). The RWPs showed transport leading in to the afternoon of May 25 that agreed with the ozonesonde winds launched at HU-Beltsville and the backwards trajectories portrayed in Figure 37. Thus, similar days examined would need to include northwesterly winds above the surface, surface high temperatures near 90°F and surface high pressure centered southeast of Maryland with slight ridging above the surface over Maryland.

To isolate these days from the past five years, days in May reaching at least 85°F at BWI airport were identified. On these days, those when morning aloft winds (using the 12 UTC [8am] sounding from Sterling, Virginia) were from the Northwest (>295° and <335°) at 850mb (approximately 1,500m) narrowed the group of days further. Finally, those days subjectively matching the pattern on May 25 and 26, 2016 over the eastern US determined the final group of days used for similar day comparisons. Twenty-six days in May of 2012-2016 were identified, not already connected or adjacent to the smoke event of 2016, which had high temperatures reaching at least 85°F at BWI. Of these 26, only six (6) were found which satisfied the northwest flow at 850mb criteria and of these six, only three days also matched the pattern of high pressure over the southeast US with a ridge axis extending in to the Midwest or western Mid-Atlantic, similar to the 2016 event (Table 7).

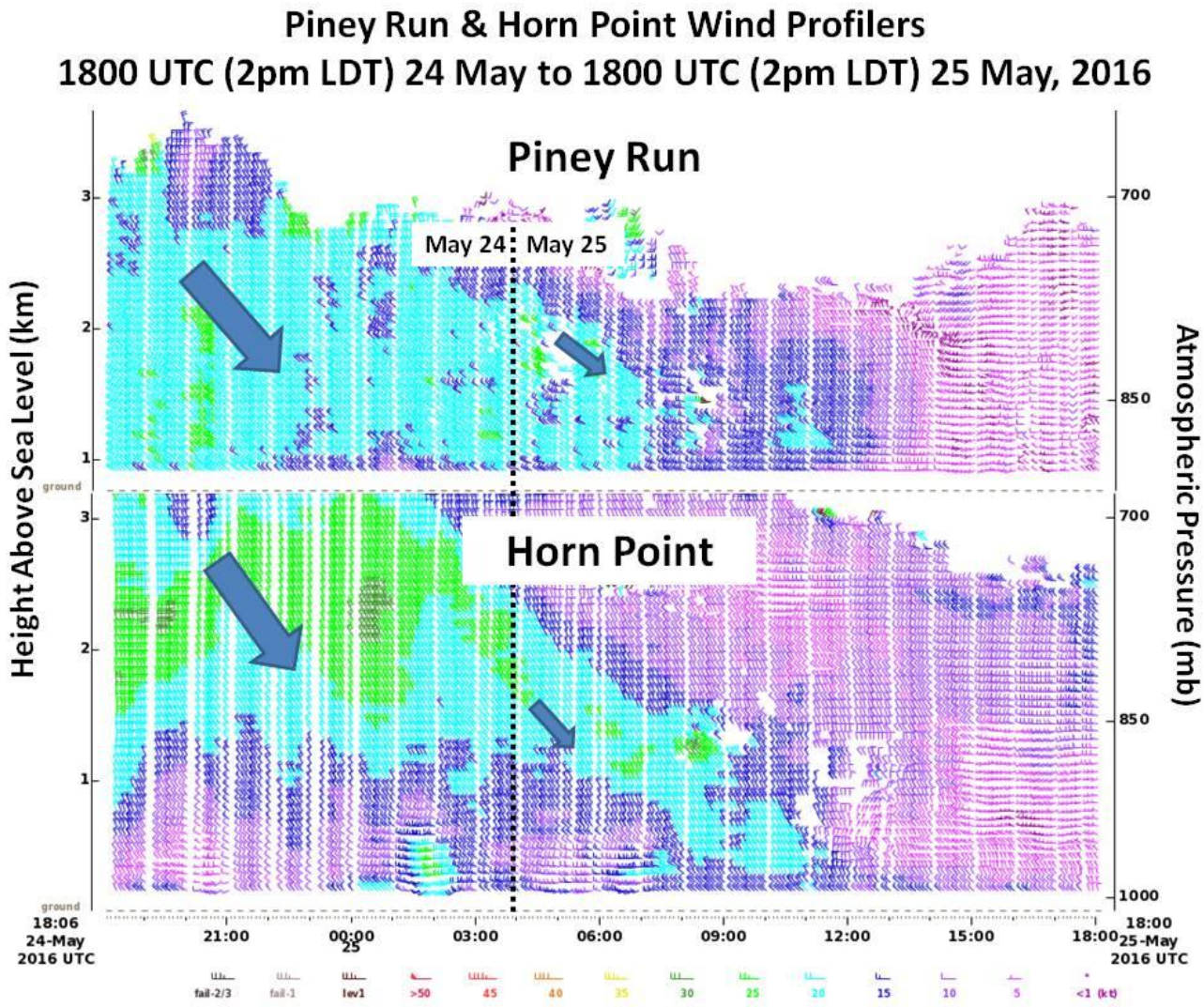
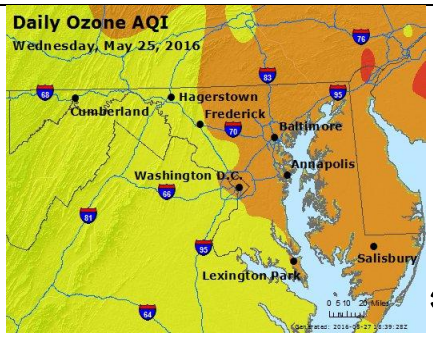
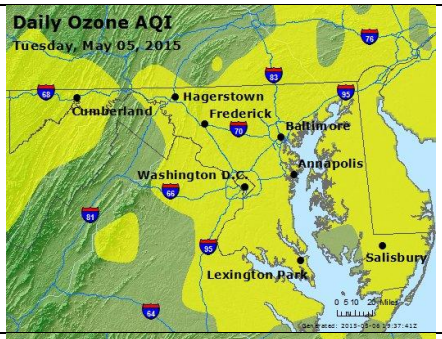
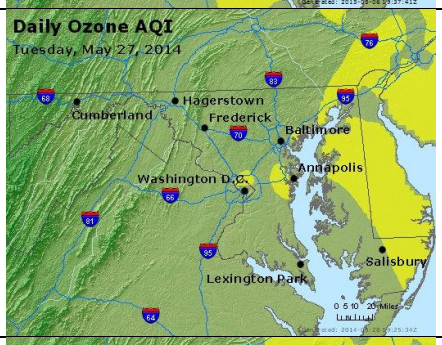
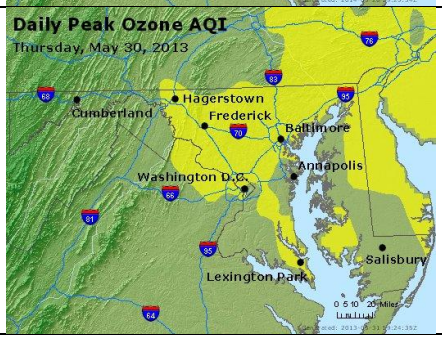


Figure 54. Radar Wind Profiler (RWP) output from 1800 UTC (2pm LDT) on May 24 through 1800 UTC (2pm LDT) May 25, 2016. The two profilers, which are on either end of the state (Piney Run is in far western Maryland and Horn Point is on the eastern shore of Maryland) both indicate robust northwest flow which is more in agreement with the ozonesondes than HYSPLIT trajectories run backwards from the afternoon on May 25, 2016.

Based on the similar day analysis, no other day in May from 2012 - 2016 which had similar meteorological characteristics produced similar levels of ozone. The highest ozone on May 25, 2016 was 85ppb, which nearly qualified as an "unhealthy" AQI day based on the 2015 standard. The next highest MD8AO concentration on a similar day was in 2013 when temperatures 6°F warmer than in 2016 produced ozone which was 11ppb lower. Spatially none of the days are comparable to the 2016 event either. More than half of the state was under code orange conditions in 2016 when in the 2013 case only four monitors were above 70ppb, in 2014, none, and in 2015 only two. This analysis reveals that similar meteorological conditions in previous years did not produce as much ozone as in 2016 despite decreasing NOx emissions over the entire period, and the lowest anthropogenic precursor emissions occurring in 2016. Thus, analog

evidence suggests the late May 2016 exceedance event was not explicable by comparing it to past may events with similar meteorology, even in cases with greater NOx emissions. The only conclusion is that the May 25 and 26, 2016 ozone exceedances were due to influences from the wildfire smoke from the Fort McMurray fire.

Table 7. Similar Day Analysis for May 25, 2016.
Three dates compared to the May 2016 ozone event were chosen by a similar maximum temperature (Tmax >=85°F) at BWI airport, 850mb winds from the northwest (>295° and <335°) on the 12 UTC (8am LDT) Sterling VA sounding and matching synoptic pattern characterized by high pressure over the southeastern US and a ridge axis across the western Mid-Atlantic or Midwest. * Due to the change in the ozone standard, the AQI color scale on the 2016 map is based on orange being greater than 70ppb and red greater than 85ppb for MD8AO.

DATE	Ozone (ppb)	T_{max} (°F)	Mapped AQI
May 25, 2016	85	86	 *
May 5, 2015	72	85	
May 27, 2014	69	90	
May 30, 2013	74	92	

4. The Occurrence was a Natural Event

According to the Clean Air Act (CAA) and the Exceptional Events Rule (40 CFR 50), an exceptional event must be "an event caused by human activity that is unlikely to recur at a particular location or a natural event." The EPA also believes that treating all wildfires on wildland as natural events is consistent with the CAA and Exceptional Events Rule. Based on the documentation provided in section 2 of this submittal which discusses the origin and evolution of the wildfire events, the Fort McMurrary fire qualifies as a natural event because non-prescribed human activity was suspected as the cause of the unplanned fire event which occurred on wildland. While the city of Fort McMurray itself was not wildland, ozone exceedances occurred 20 days after the fire roared through the town. Therefore wildfire emissions affecting ozone concentrations in Maryland were generated predominantly from sparely populated forested areas, meeting the definition of wildland. The EPA generally considers the emissions of ozone precursors from wildfires on wildland to meet the regulatory definition of a natural event at 40 CFR 50.1(k). Accordingly, the MDE has shown that the event is a natural event and may be considered for treatment as an exceptional event.

5. The Occurrence was Not Reasonably Controllable or Preventable

Based on the documentation provided in section 2 the fires relevant in this demonstration were likely due to human activity. Unintentional or not, these fires were considered natural wildfire events by the EPA, were outside of the United States, and were therefore neither reasonably controllable or preventable by the state of Maryland. No policy that Maryland enacted could have prevented the fire or the smoke which it caused, to enter the United States or Maryland. MDE was not aware of any evidence clearly demonstrating that prevention or control efforts beyond those actually made would have been reasonable. Therefore, emissions from these wildfires were not reasonably controllable or preventable and meet the criterion for treatment as an exceptional event.

6. Public Comment

MDE posted notice of this exceptional events demonstration on May 26 on the MDE website for a comment period of 30 days**.** [Number] public comments were received and have been included in [Section X] of the exceptional event demonstration, along with MDEs responses to these comments.

7. Conclusions

On May 25 and 26, 2016 smoke associated with wildfires predominantly located near Fort McMurray, Alberta, Canada occurred that generated NOx and VOC ozone precursors within the fire's smoke plume which moved across the north central CONUS and Great Lakes by May 21, 2016. This smoke plume was subsequently transported east and southeastward towards Maryland and impacted all monitoring sites across Maryland's air monitoring network. The monitored MD8AO concentrations reached 84 and 85 ppb on May 25 and 26, respectfully, and resulted in at least one of the fourth highest concentrations of 2016 at 18 of 20 sites and met or beat the 99th percentile at 16 sites on at least one or both of the days. The

comparisons and analyses, provided in sections 2 and 3 of this demonstration support MDE's position that the Fort McMurray wildfire event affected air quality in such a way that there exists a clear causal relationship between the specific event and the monitored exceedances on May 25 and 26 and thus satisfies the clear causal relationship criterion.

The analyses provided in this demonstration support MDE's position that the Fort McMurray wildfire affected air quality in such a way that there exists a clear causal relationship between the event (Fort McMurray fire) and the monitored ozone exceedances in Maryland on May 25 and 26, 2016 and thus satisfies the clear causal relationship criterion for recognition as an exceptional event. Based on these facts, MDE requests that EPA concur that the 28 MD8AO concentrations between May 25 and 26, 2016 (Table 8), exceeding the 70ppb NAAQS at the following 16 monitors: Aldino (240259001), Calvert (240090011), Edgewood (240251001), Essex (240053001), Fair Hill (240150003), Furley (245100054), Glen Burnie (240031003), Horn Point (240190004), HU-Beltsville (240330030), Millington (240290002), Padonia (240051007), PG Eq Cntr (240338003), South Carroll (240130001), S. Maryland (240170010), and the two CASTNET sites – Beltsville (240339991) and Blackwater NWR (240199991), were impacted by an exceptional event. MDE formally requests that the data from these 16 monitors on these days be flagged as such and be excluded from use for regulatory determinations.

Table 8. The 16 ozone monitors at which MDE is seeking EPA concurrence for data exclusion of event influence air quality data. Local names and Air Quality System (AQS) identification numbers (AQSID) identify monitors in the text. Also given are the maximum daily 8-hour average ozone (MD8AO) concentrations in ppb along with that day's rank in the 2016 season in parentheses. A rank of (1) indicates the MD8AO was the highest recorded at that site in the season. The final columns indicate the design value with no exclusion of data (Including) and if both May 25 and 26 are excluded from design value calculations (Excluding). Sites with an asterisk indicate the site does not have a valid design value in 2016. Green highlighting indicates the monitors which MDE seeks exemption, based on the 4th high rankings. Cells showing "-" are MD8AO at sites which did not exceed 70ppb and therefore cannot seek exclusion.

		2016					
SiteName	AQSID	MD8AO [ppb] (rank)		Fourth High [ppm]		Design Value [ppm]	
		May 25	May 26	Including	Excluding	Including	Excluding
Aldino	240259001	77 (3)	79 (2)	0.077	0.076	0.073	0.073
Beltsville CASTNET	240339991	76 (2)	72 (3)	0.070	0.070	0.068	0.068
Blackwater NWR CASTNET	240199991	-	76 (1)	0.068	0.068	0.066	0.066
Calvert	240090011	-	75 (1)	0.070	0.069	0.069	0.068
Edgewood	240251001	79 (4)	80 (2)	0.079	0.079	0.073	0.073
Essex	240053001	78 (4)	81 (2)	0.078	0.077	0.072	0.072
Fair Hill	240150003	83 (2)	76 (5)	0.080	0.076	0.076	0.074
Furley	245100054	75 (4)	78 (2)	0.075	0.068	0.069	0.066
Glen Burnie	240031003	75 (6)	76 (4)	0.076	0.076	0.076*	0.076*
Horn Point	240190004	71 (2)	77 (1)	0.067	0.067	0.064	0.064
HU-Beltsville	240330030	74 (2)	74 (2)	0.070	0.069	0.069	0.068
Millington	240290002	85 (1)	76 (2)	0.072	0.069	0.070	0.069
Padonia	240051007	74 (3)	84 (1)	0.073	0.073	0.072	0.072
PG Eq Cntr	240338003	74 (5)	-	0.076	0.076	0.071	0.071
South Carroll	240130001	72 (4)	75 (2)	0.072	0.068	0.068	0.067
S. Maryland	240170010	-	73 (4)	0.073	0.073	0.070	0.070

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Appendix: A

Letter of request to EPA CAMD to flag CASTNET monitors in Maryland.

Maryland
Department of
the Environment

Larry Hogan
Governor

Boyd Rutherford
Lieutenant Governor

Ben Grumbles
Secretary

May 4, 2017

Timothy Sharac
USEPA Headquarters
William Jefferson Clinton Building
1200 Pennsylvania Avenue, N.W.
Mail Code: 6204M
Washington D.C. 20460

Tim

Mr. Sharac,

MDE requests placement of RF data flags indicating the influence of Canadian wildfire smoke on air quality be placed on the two CASTNET monitors residing in Maryland. The dates and times at the following sites are as follows:

- Beltsville (240339991):

  May 25, 2016, hour 0 to May 26, 2016, hour 23
  July 21, 2016. hour 0 to July 22, 2016, hour 23

- Blackwater NWR (240199991):

  May 25, 2016, hour 0 to May 26, 2016, hour 23

Per the requirements to pursue data exclusion, the EPA requires flagging of data prior to submitting an exceptional event demonstration package to the EPA. Maryland is finalizing demonstrations showing the impact of two wild fires on the regulatory monitor sites. In May, fires near Fort McMurray, Alberta lofted a smoke plume which impacted ozone concentrations across the entire state of Maryland and much of the northeast US. In July, a large number of fires in aggregate across northwestern Canada lofted a smoke plume which again subsided over the northern Mid-Atlantic. Both instances were tied to ozone exceedances of the 70ppb NAAQS in Maryland. Maryland has determined exclusion of these data points will impact current and future design values and possibly the future attainment status of the state.

Sincerely,

DeKr

David Krask
Manager, Ambient Air Monitoring Program

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Appendix: B

Table 9. Ozone monitors at which MDE recognizes potential impacts on future year designations. Table description is identical to Table 8.

SiteName	AQSID	2016					
		MD8AO [ppb] (rank)		Fourth High [ppm]		Design Value [ppm]	
		May 25	May 26	Including	Excluding	Including	Excluding
Blackwater NWR CASTNET	240199991	70 (3)	-	0.068	0.067	0.066	0.065
Calvert	240090011	70 (4)	-	0.070	0.068	0.069	0.068
Frederick	240210037	70 (4)	-	0.070	0.067	0.067	0.066
Rockville	240313001	69 (2)	-	0.068	0.068	0.068	0.068

These monitors did not exceed 70ppb on May 25 or 26, 2016. However, they observed MD8AO concentrations which were within the fourth highest of the season. Therefore, exclusion of these data points could lower future year DVs since they depend on the fourth highest over three years. Exclusion of these data points, even though they are not above 70ppb could lower these monitor's DV for the next 3 years.